Learning to Stand with a Simulated Prosthesis

Undergraduate Honors Thesis

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by

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ABSTRACT

Learning to stand and balance is one of the most important processes that human children go through as they become independent competent movers. However, the process that humans use to learn to stand stably has not been studied in sufficient detail. Certain amputees, stroke victims, and other people with movement disorders may need to re-learn how to stand. Understanding this re-learning process better may help design better rehabilitation procedures for such populations. Here, we study such re-learning process by using a simulated prosthesis, which can be used with healthy adults to cause a similar learning process. The purpose of this research is to collect data on how people learn to stand and balance with a simulated prosthesis and then mathematically model the process of learning to be more stable. First, data is collected on healthy human subjects standing from sitting and performing quiet standing using a Vicon 3D motion capture system and a force plate. The subjects are then outfitted with a simulated prosthesis called the iWalk 2.0 and again stand from sitting and perform quiet standing and the data will be recorded. This data is then analyzed in MATLAB to create a mathematical model of the learning process. Specifically, we first determine how humans modulate their leg forces to control their body state. Then, we characterize the re-learning process by observing how the feedback gains in this "standing controller" change as the subjects become more experiences with the simulated prosthesis. All subjects participated with informed consent and the experimental protocol approved by the Ohio State IRB. Current results point to the subjects initially not loading the prosthesis and gradually loading the prosthesis. The subjects had more force variability (standard deviation) initially, suggesting that they initially required a lot of control; their later force variability was lower, suggesting a more stable and learned steady state. Further work will be needed to model the learning process, but the results point to the subjects becoming more stable and learning how to

balance with the prosthesis over the course of the trial. Amputee and stroke victims need assistance relearning to stand, and by understanding the learning process we can provide insight into this.

Acknowledgements

Thank you to Professor Srinivasan for his guidance in this research. Thank you to Varun Joshi for his assistance in laboratory setup. Special thanks to my wife for her patience and support as I completed this research.

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Chapter 1: Introduction

1.1 Background Information

Nearly all humans learn to walk by the age of 16 months and continue to walk well into old age. People that suffer amputations to their legs and are fitted with prostheses also relearn to walk. Many manage to do so in a much shorter time frame than infants (after the leg has healed and pain has subsided). In addition, some lower leg injuries result in the use of casts or smaller orthoses that the patient is able to adapt to and walk on rapidly. How are humans, who spend so long on learning how to walk initially, able to adapt to changes to their lower body structures so quickly? Here, we study how humans are learn to adapt to an introduced prosthesis. In our experiment we use an iWalk 2.0 device (Figure 1.01) to simulate a unilateral prosthesis.

Figure 1.01: Non-amputee wearing iWalk device, usually used for taking the load of an injured foot.

In the following few paragraphs, to provide further background and context to this thesis, we briefly review the literature on how children learn to walk, on how adults learn after a surgery or disease, and on the stability and control of standing.

Children learning to walk. Why study the process of learning how to balance and walk? Due to the difficulties in capturing every moment of an infant's life while they are learning how to walk, there is much that is not understood about the dynamics of how children learn to walk. However, many studies have focused on balance and motion of older children. Prior studies have focused on the total motor development of children from walking to drawing and competitive sports (Cratty, 1979). Other studies have focused on how visual impairment affects motor control and balance in children (Pereira, 1990) or whether infants are learning how to walk versus learning dynamic postural control (Bril & Brenière, 1993). Several studies have focused on children with cerebral palsy and how that disorder affects gait and balance, with one study separating balance from gait for the purpose of increasing understanding of cerebral palsy (Rose et al., 2002).

These studies did not focus on the process of learning how to walk, but more on general motor control and balance by focusing on the trunk. Of these, only Bril & Brenière (1993) go in depth on the process of learning how to walk, but for the intent of comparing it to learning postural balance. Learning to stand may be a critical process in learning how to walk and faces similar difficulties in monitoring infants as they learn how to stand.

Learning, adaptation, and rehab after surgery or disease. Stroke victims can have difficulty recovering their ability to walk, and regaining the ability to walk is a common goal of stroke patients (Bohannon et al. 1991). In a study on how stroke patient recover their walking function, initially 51% could not walk, and 12% could walk with assistance (Jørgensen et al. 1995). After rehabilitation only 18% could not walk and 11% could walk with assistance (Jørgensen et al. 1995). With 29% of the subject population still having mobility impairment after rehabilitation, there is room for improvement in rehabilitation protocols. In addition to walking, stroke victims have difficulty with standing balance, showing large amounts of sway and general instability (De Haart et al. 2004). Understanding the way that humans learn how to balance could help to improve rehabilitation procedure and decrease the amount of people with mobility impairment after completing rehabilitation.

Standing balance. The mechanics of standing balance is similar to that of an inverted pendulum on a moving platform, with the pivot at the ankle joint, length equal to the distance from the ankle joint to the center of mass and a mass equal to the body mass of the human (Kooij et al 2005). The inverted pendulum is subjected to many internal and external forces such as changing base, breathing, body movement, and gravity (Kooij et al 2005). Achieving human standing balance despite these forces requires a closed feedback loop. As the body moves, its center of pressure (COP) and center of mass (COM) displacement varies (Winter et al. 1998). By observing the magnitude, frequency and standard deviation of COM and COP excursions you can quantify human balance (Winter et al. 1998). Interestingly enough, when balancing, the human control system aims to use minimal muscle use to stabilize balance (Kiemel et al. 2011) as opposed to minimizing center of mass or center of pressure excursions which is considered a measure of balance. While the mechanisms of human balance are well explored, how the body learns and tunes these systems is not, which is part of the motivation for this study.

1.2 Purpose of Study:

Here, we propose to study how a healthy non-amputee human learns to stand while wearing a "simulated" unilateral or bilateral prosthesis. Understanding the principles underlying such learning may help inform better rehabilitation procedures and also provide a quantification of mobility improvements. In addition, understanding how a person learns to balance with a prosthesis will help to uncover the processes behind learning to walk with a prosthesis. The goals of this study are as follows:

- Collect center of pressure, sway, balance and motion capture data on how people learn to stand and balance with an introduced prosthesis.
- Mathematically model the process of how the subjects learned to stand and balance with an introduced prosthesis in order to provide a foundation for future research on how humans learn to walk with a prosthesis.

1.3 Significance of Study:

The significance of the study is twofold. First understanding the principles of learning to stand and balance may help create better rehabilitation procedures for those who are mobility impaired. With 16.1% (39.5 million) adults in the United States having difficulty with any physical function and of that 7% (17.1 million) having difficulty or being unable to walk a quarter mile, there is a significant portion of the population that could benefit from improved rehabilitation to restore their mobility (Blackwell and Villarroel 2018). In addition to the improvements to rehabilitation procedures that could result, no studies to date have focused on how adults learn to balance immediately following the addition of a prosthesis, nor have they documented the process using motion capture.

1.4 Overview of Thesis:

This thesis has four chapters. Chapter 2 discusses the experimental methods, subject population and data processing procedures. Chapter 3 discusses the results of these experiments.

This includes detailed description of what the data results mean and the data among the subjects relates overall. Chapter 4 summarizes the key conclusions of this thesis, contains discussion on the applications of work and outlines directions for future research.

Chapter 2: Methods: Experiments, Data Analysis, and Models

This chapter outlines the experimental procedures used to characterize the process a subject uses to learn how to stand and balance with a prosthesis, and then outlines the subsequent processing of the experimental data.

2.1 Experiment Outline and Setup

An experimental protocol was created for having the subjects stand with and without a simulated prosthesis. The protocol was approved by The Ohio State University Institutional Review Board. Subjects were given minimal instruction on the objective of the experiments. First, anthropometric data such as leg length, age, sex, and weight were recorded. In each trial without the simulated prosthesis, five markers were strapped to the subject's waist, four markers were strapped to each thigh, four markers were strapped to each shin and three markers were attached to each subject's foot. The subject started seated on an instrumented split-belt treadmill (with six-axis load cells). The subjects were then asked to stand up and perform quiet standing for 15 minutes. The subject could stop and take a break at any point during this process. This process is captured in figures 2.01 through 2.03.

Figure 2.01: Subject fitted with motion capture markers. Five markers were strapped to the subject's waist, four markers were strapped to each thigh, four markers were strapped to each shin and three markers were attached to each subject's foot during the trials without a simulated prosthesis.

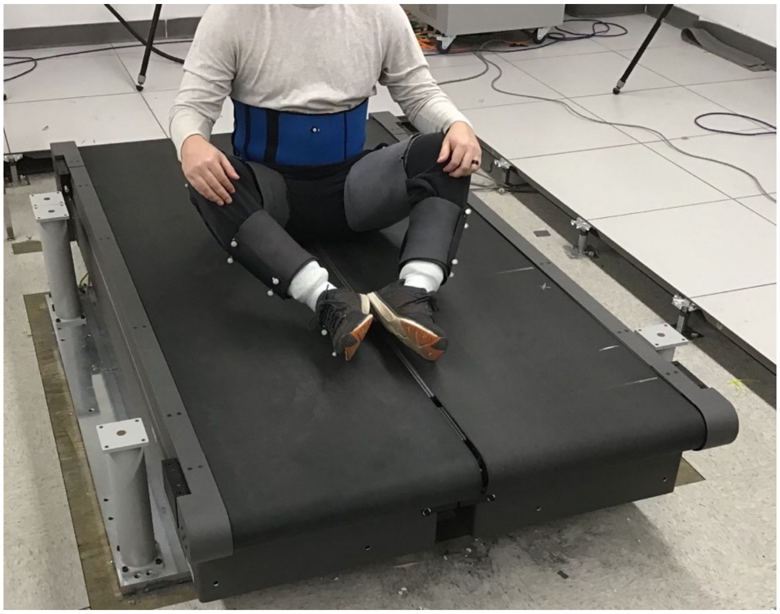


Figure 2.02: Subject seated on the force plate. The subject was instructed to stand and perform quiet standing on the treadmill. The central seating is to ensure that there is only one leg per force plate.

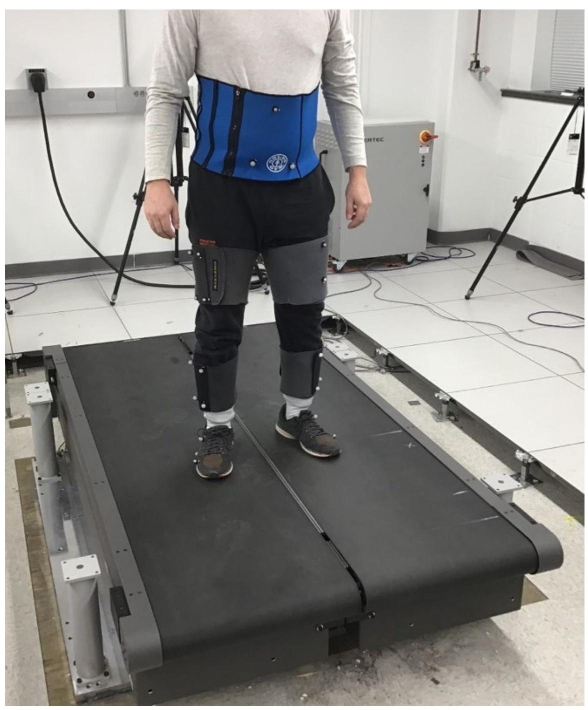


Figure 2.03: Subject performs quiet standing on the force plates. Subject stands from seated, with one foot per force plate and performs quiet standing for 15 minutes. This is to obtain a baseline to compare to prosthesis equipped trials.

Then, the subject sat back down on the instrumented treadmill and fitted with a simulated lower leg prosthesis on their right leg: specifically, we used the hands-free crutch called iWalk 2.0 (Figure 2.04), which simulated the wearing a unilateral prosthesis, as noted in Chapter 1.

Figure 2.04: iWalk 2.0 device. This is simulated prosthesis device used in these experiments. Obtaining a proper fit is crucial to the success of the experiments.

When applying the iWalk 2.0 device to subjects, obtaining a proper fit is crucial for gathering successful data. If the iWalk 2.0 is not fitted properly extra instability in the second trial due to unsecured device movement may be present. An improper fit is shown in figure 2.05 below.

Figure 2.05: Improper fit of iWalk 2.0 device. This device is fitted improperly. First the iWalk2.0 is too long causing the subject to bear more weight on the non-prosthesis leg as opposed to evenly between their legs. The knee height of the device does not match up with the subject knee height, and the device "foot" angle does not match the subject foot angle.

In order to ensure a good fit, the leg length of each subject was measured and used to size the height of the iWalk 2.0 to each subject, which allowed the device to be the proper height overall, proper knee height and proper upper leg height. To avoid error due to improper rotation of the device during fitting and loose fitting, the device was aligned while the subject was seated so that no rotation errors or loose fittings due to a standing fit would lead to. The seated fitting also preserved the subject's learning window, as during the time of a standing fit the subject would learn to balance, which is what the experiment wants to capture.

From the moment this prosthesis is attached, all movements of the subject and the external forces exerted by the subject were recorded, respectively, using Vicon motion capture system and the instrumented treadmills. Figures 2.06 and 2.07 below show the process used for the prosthesis trials of the experiment.

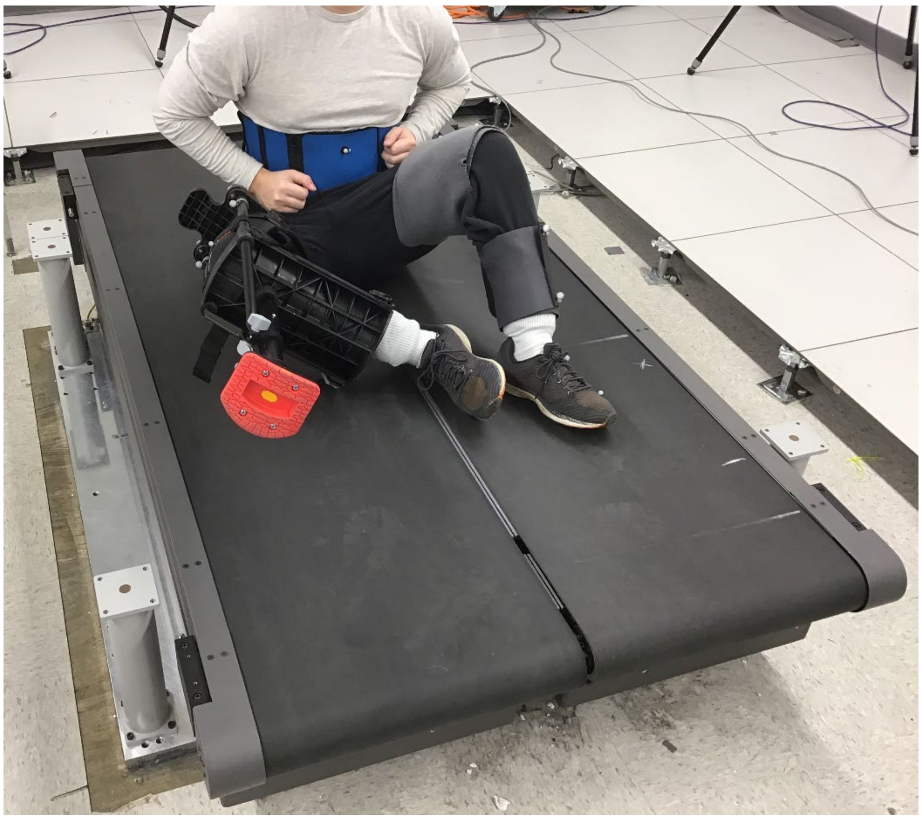


Figure 2.06: Subject seated on center of treadmill. The subject has been fitted with the iWalk 2.0 device while seated. They are seated in the center of the treadmill so that when they stand, each force plate will have one leg on it.

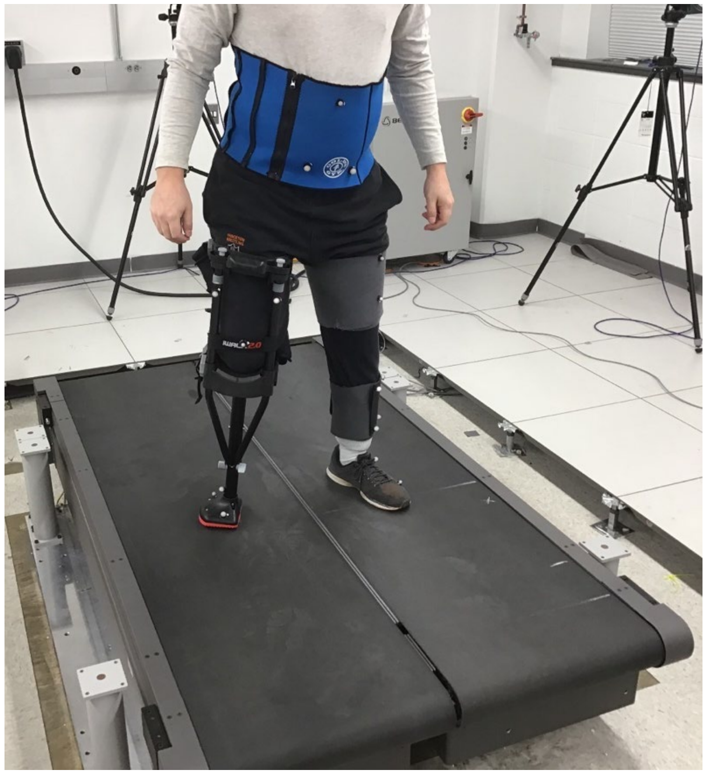


Figure 2.07: Subject performing quiet standing with the iWalk 2.0. Subject stands from seated, with one foot per force plate and performs quiet standing for 30 minutes. The Center of Pressure, the ground reaction forces and MoCap data are captured during this time to compare to the baseline trial.

During trials with a simulated prosthesis, the 4 markers on the subject's right shin and 3 markers on the subjects' right foot were removed to accommodate the simulated prosthesis, and 3 markers were placed on the "foot" of the simulated prosthesis. The subject was instructed to stand and perform quiet standing on the treadmill. The subject can stop and take a break at any point during this learning process. Due to the length of time the learning process can take, subjects were asked to perform quiet standing for 30 minutes with the simulated prosthesis.

The experiment was conducted at the movement lab, Scott W197. The room had eight motion capture (MoCap) cameras set up to capture the entire event (Vicon T20). The laboratory setup is shown in figure 2.08.

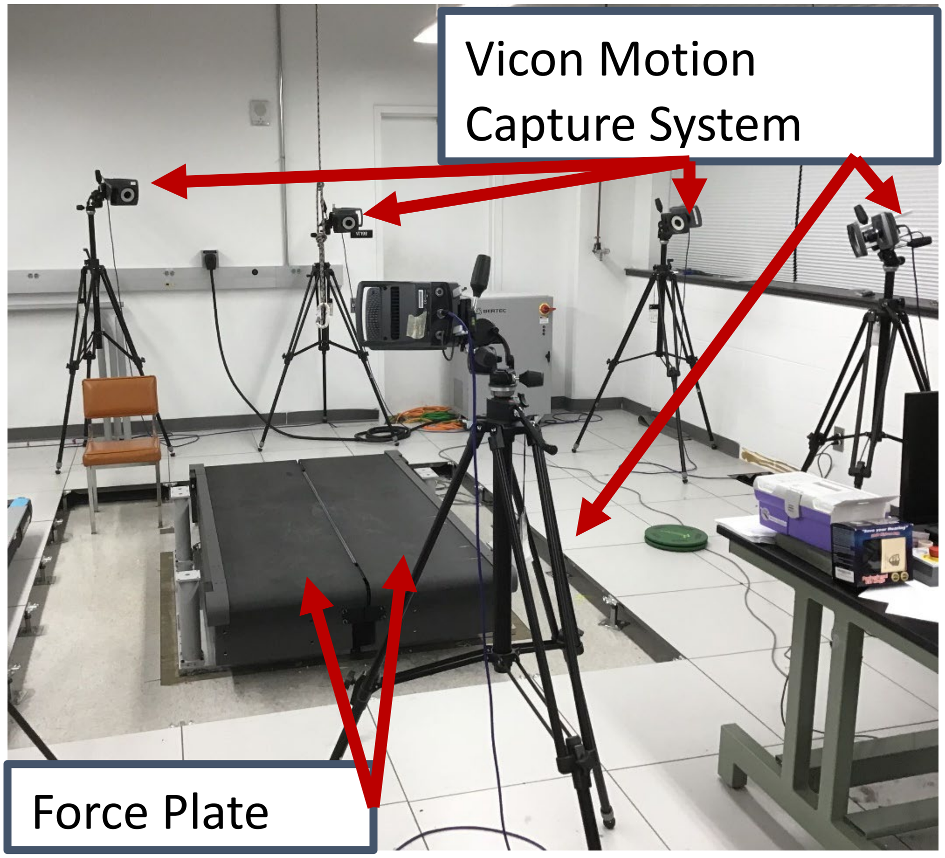


Figure 2.08: Movement Lab setup. Eight Vicon motion capture cameras were setup to cover all angles of the subject's motion. In addition, two force-plates in the center captured the COP and reaction force data.

The MoCap markers are tracked by the cameras (at 100Hz) and can be processed to find the [x,y,z] point of the markers with respect to an origin on the treadmill surface. For calibrating the MoCap cameras, a standard calibration rod was used to create a ground frame of reference. The calibrated motion capture data had a measurement uncertainty of less than 1 mm. The split-belt treadmill measures 3D force and moment exerted on each belt at a 1000 Hz sampling rate.

2.2 Subject Population

Seven subjects completed the experiments. There were 4 male subjects and 3 female subjects. The mean of subjects' mass was 70.27 kg with standard deviation of 8.47 kg. The mean of subjects' leg length was 0.911 m with standard deviation of 0.065 m. The mean age of subjects' age was 21 years, with a standard deviation of 0.8165 years. All subjects participated with an informed consent about their role in this experiment.

Criteria for Inclusion: Healthy adults of either sex with no cardiovascular issues or movement disorders.

Criteria for Exclusion: People who are not able to stand for up to an hour consecutively, people who are unable to stand independently, people who are pregnant, people with a history of heart or lung problems and people with other movement disorders were not considered for this experiment.

2.3. Data Processing

Data consisted of x, y, z position of all the reflective markers (100 Hz), the 3D forces (1000 Hz) that the legs apply on each treadmill, and the centers of pressure (CoP) of the two feet on their respective belt. First, data was imported into MATLAB and CoP data points corresponding to force in the Z direction of less than 30 N were removed. This is because with less force than about 30N on the treadmill in the Z direction, the treadmill is reporting noise, not an accurate representation of the forces or position of the subject's CoP. These times of unreliable CoP corresponded to when the subject re-adjusted their positioning by lifting up a foot. Second, the data was smoothed using the smooth() function in MATLAB (windowed moving average) to remove noise, and separated into 30 second windows. The average and standard deviation of the measured quantities were calculated for each complete trial, as well as for the 30 second windows.

We hypothesized that the horizontal forces on each leg will be used in a manner consistent with a proportional derivative controller to control the center of mass of the person. For instance, $F_x = -k_p(x - x_{\text{desired}}) - k_d(\dot{x})$, where F_x is a sideways force on a leg, x is sideways center of mass position, x_{desired} is the reference center of mass position desired by the control system, and k_d and k_p are, respectively, the proportional and derivative gains on this putative feedback controller. We can add a delay terms to this equation to model transmission latencies and other dynamics. We determine x and $\dot{x}$ by integrating $\ddot{x} = F_x/m$, where m is total body mass, but can also be obtained approximately from marker data. The fitlm() function was used on the overall to fit a linear regression model to the overall data to derive the regression coefficients k_d and k_p. The fitlm() was used on each bucket of data to determine the change in regression coefficients over the course of the trial. The standard deviation was also calculated for each bucket over the course of the trial. While the early calculations were performed to infer such time-varying feedback gains, we do not present these in detail this thesis, leaving such presentation for future work.

Chapter 3: Results and Discussion

This chapter summarizes the trends in the different mechanically relevant quantities as the subject learns to stand on the iWalk device, providing an interpretation of these trends (or the lack thereof) from the perspective of the subject learning to stand "better" with the device.

3.1 Forces in the Z Direction

Vertical force on prosthesis is different finally versus initially versus overall. Table 3.01 contains the averages of the force in the vertical (Z) direction during the baseline and prosthesis trials. There is a difference in the total force between the two columns (about 20 N), which is consistent with the weight of the iWalk device, providing a check of the resolution of the force sensors. Table 3.02 shows the forces borne by the right and the left leg in both the baseline and in the prosthesis conditions. Most subjects start with less than 50% of their weight borne by the prosthesis in the initial 30 seconds. We see that all subjects except one shifted more of their weight to the right leg which had the prosthesis in the prosthesis trial overall. That is, subjects had more weight on the limb with the iWalk 2.0 during the final 30 seconds of the trial with the prosthesis than the initial 30 seconds of the trial with the prosthesis. This could be one of the intended designs of the iWalk 2.0 device as it acts like a crutch to support additional weight while the other leg mainly contributes to balancing.

Vertical force variability changes initially versus finally. Table 3.03 has the standard deviations of the ratios from Table 3.02. The standard deviations overall were higher in the prosthesis trial than in the non-prosthesis trial, which is expected as the prosthesis would cause more instability. The standard deviation during the prosthesis trial decreased from the first 30 seconds to the last 30 seconds, which suggests that the subjects were more stable and better at balancing than they were initially.

Table 3.01: Average Z-Force during baseline and Prosthesis Trials. This table contains the averages of the forces in the Z direction during the trials. This reflects the total weight of the subject or the total weight of the subject plus the weight of the prosthesis.

Subject Number	Z-Force Sum Baseline	Z-Force Sum Prosthesis Trial
1	646.51	666.25
2	574.93	595.81
3	759.42	779.69
4	721.08	740.51
5	838.71	855.36
6	706.16	728.08
7	708.77	731.5

Table 3.02: Ratio of Z-Force on Right Leg. This table has sections on the ratio during the non-prosthesis, prosthesis, and first and last 30 seconds of the prosthesis trial. The ratio of force on the right leg increases during the prosthesis trial overall but decreases at the end.

Subject Number	Baseline Ratio of Z-Force on Right Leg	Prosthesis Trial Ratio of Z-Force on Right(Prosthesis) Leg	Prosthesis Trial Ratio of Z-Force on Right (Prosthesis) Leg First 30 secs	Prosthesis Trial Ratio of Z-Force on Right (Prosthesis) Leg Last 30 secs
1	0.4795	0.5279	0.3540	0.5516
2	0.4707	0.6972	0.4968	0.7102
3	0.4808	0.6044	0.4121	0.6622
4	0.5361	0.5488	0.4043	0.5642
5	0.4641	0.3696	0.2954	0.3919
6	0.4731	0.5289	0.3980	0.5342
7	0.5713	0.6234	0.5134	0.6437

Table 3.03: Standard Deviation of Ratio of Z-Force on Right Leg. This table has sections on the standard deviation of the ratio of Z force on right leg to overall force during the non-prosthesis, prosthesis, and first and last 30 seconds of the prosthesis trial. The standard deviation increases during the prosthesis trial overall but decreases by the end of the prosthesis trial.

Subject Number	Standard Deviation of Baseline Ratio of Z-Force on Right Leg	Standard Deviation of Prosthesis Trial Ratio of Z-Force on Right(Prosthesis) Leg	Standard Deviation of Prosthesis Trial Ratio of Z-Force on Right (Prosthesis) Leg First 30 secs	Standard Deviation of Prosthesis Trial Ratio of Z-Force on Right (Prosthesis) Leg Last 30 secs
1	0.0232	0.112	0.1114	0.0549
2	0.0325	0.0688	0.1423	0.0544
3	0.0133	0.0551	0.1398	0.0122
4	0.0178	0.0572	0.0806	0.0127
5	0.0203	0.0481	0.1011	0.0900
6	0.0195	0.0381	0.1285	0.0158
7	0.0196	0.0297	0.1162	0.0041

Average Ratio of Z Force on Prosthesis Across All Subjects. Figure 3.01 (below) shows the ratio of force in the Z direction that was applied to the leg equipped with the prosthesis. Similar to the data from the tables, we see that over the course of the trials, across all subjects, they initially do not put much force on the prosthesis, and then over the course of the trial begin to apply more weight to the prosthesis, settling near a ratio of 0.6. In future work, we wish to model this learning process as a first or a higher order process and capture the time-constants of the various key processes.

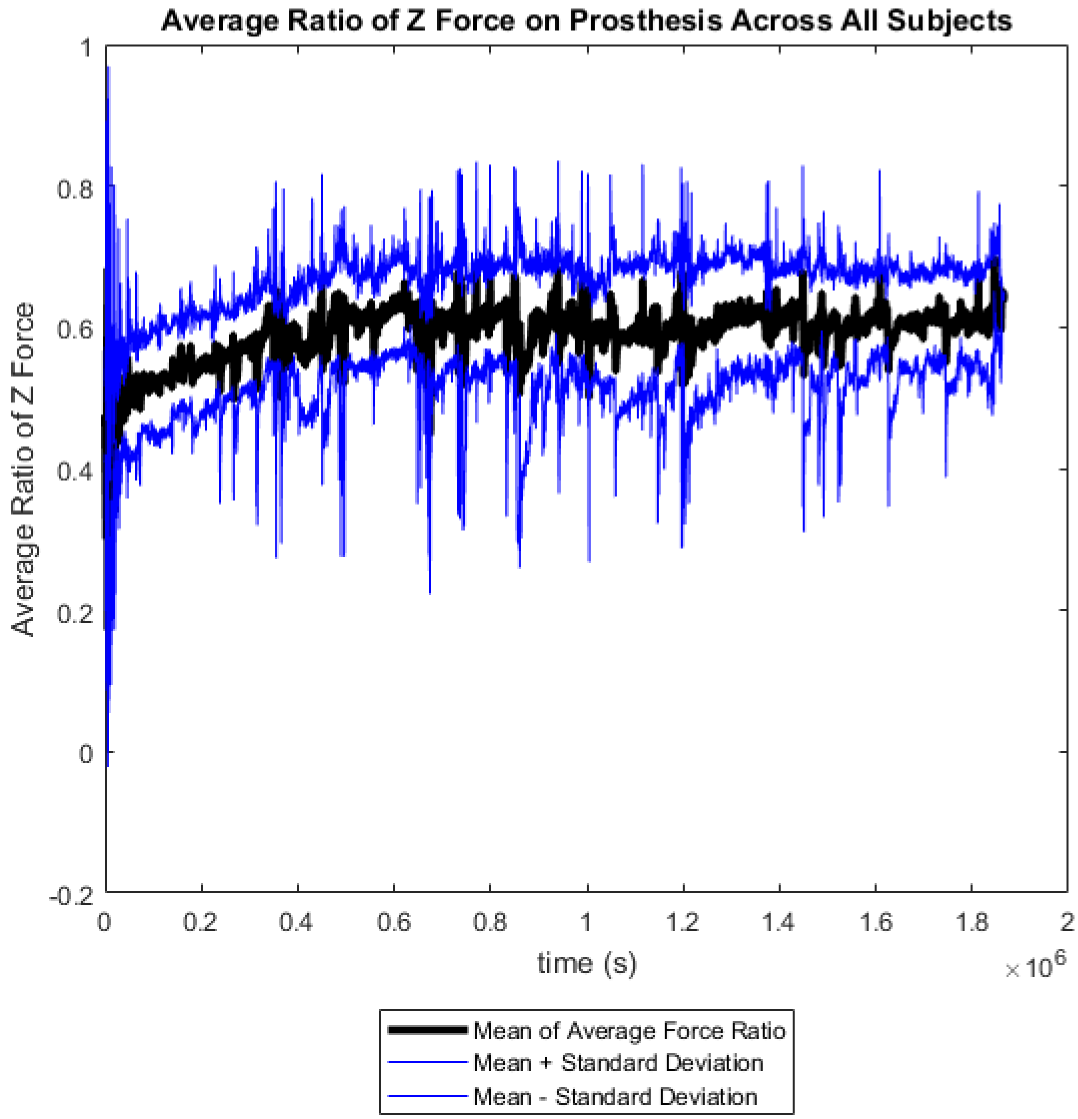


Figure 3.01: Average Ratio of Z Force on Prosthesis Across All Subjects Over Time. This is a graph of the average force on the prosthesis. Subjects started with less weight on the prosthesis and over the course of the trial increased the ratio of weight on the prosthesis to around 0.6 of the total force in the Z on the prosthesis.

Vertical force compared to non-prosthesis trial. Figures 3.02 through 3.08 (below) show the force in the Z direction during the prosthesis trial compared to the baseline non-prosthesis trial average and standard deviations. None of the subjects stabilized their weight distribution in similar bounds as their baseline trials. This suggests that subjects adopted a new weight distribution when using the iWalk 2.0 device, which is consistent with the data from Tables 3.01 and 3.02.

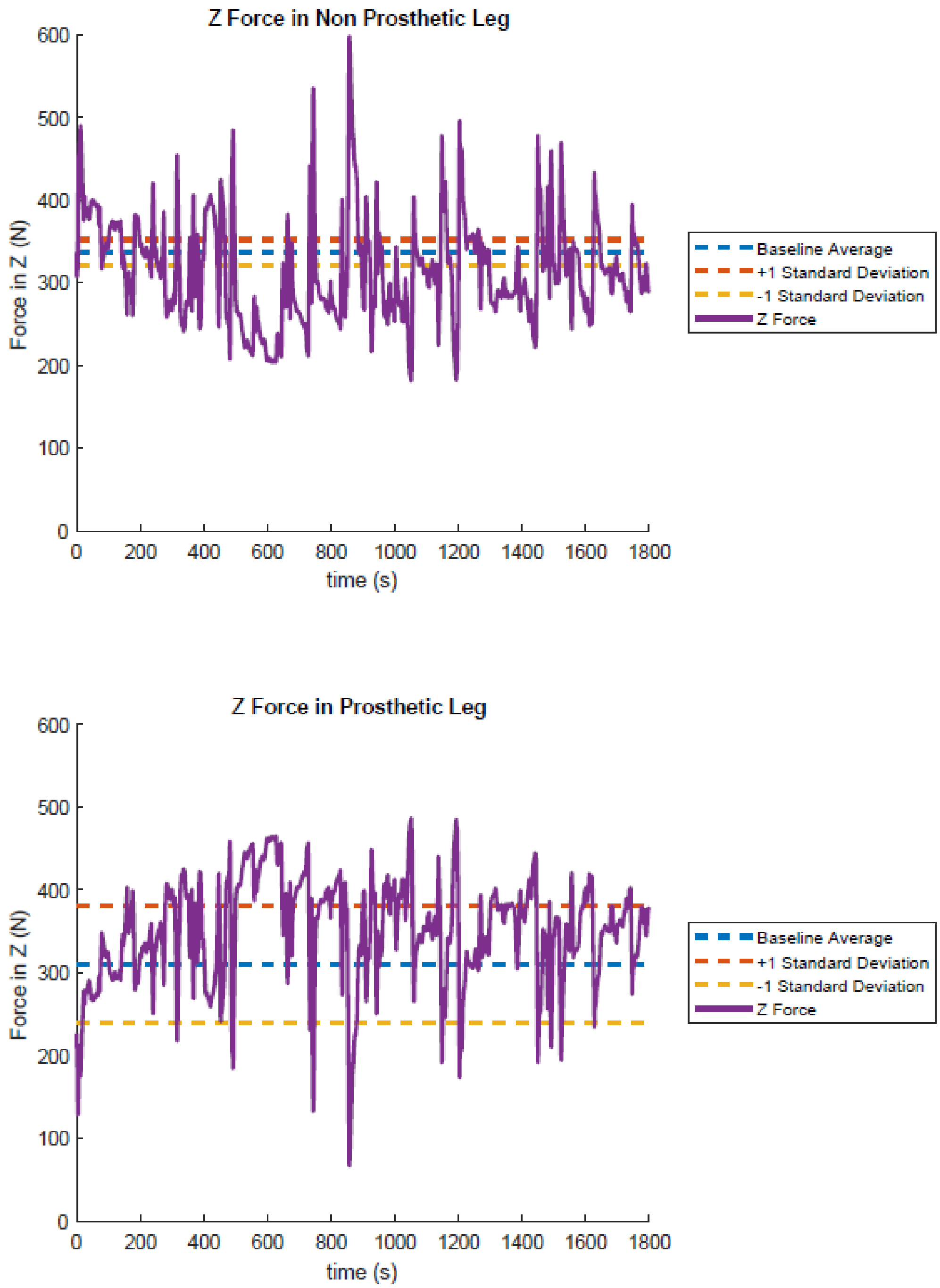
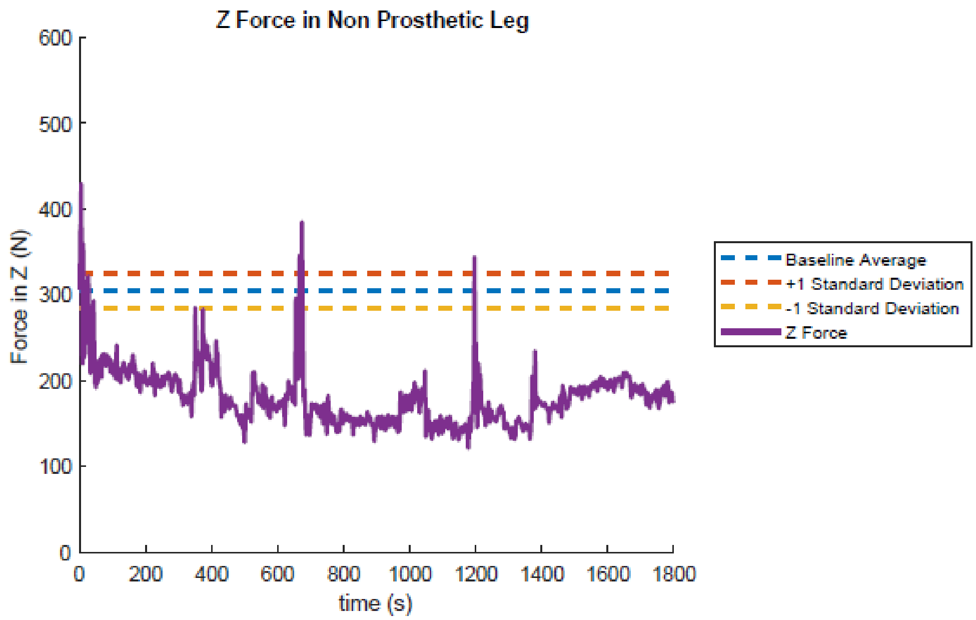


Figure 3.02: Force in the Z direction during prosthesis trial, compared to the baseline average for subject 1. The force in the Z direction does not appear to stabilize within the standard deviation of the baseline trials. This suggests a change in standing weight distribution caused by the introduced prosthesis.



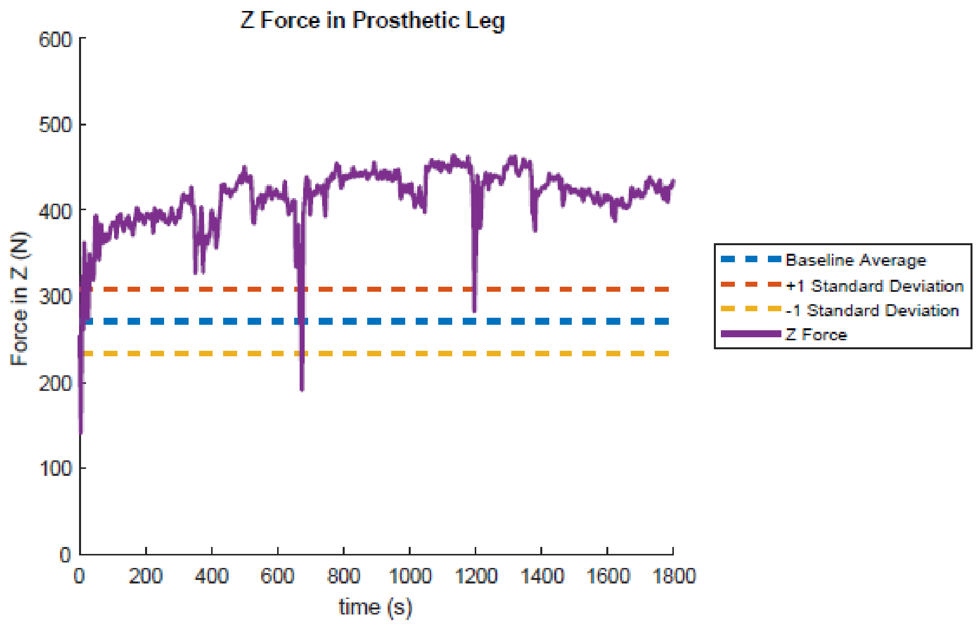


Figure 3.03: Force in the Z direction during prosthesis trial, compared to the baseline average for subject 2. The force in the Z direction does not appear to stabilize within the standard deviation of the baseline trials. This suggests a change in standing weight distribution caused by the introduced prosthesis.

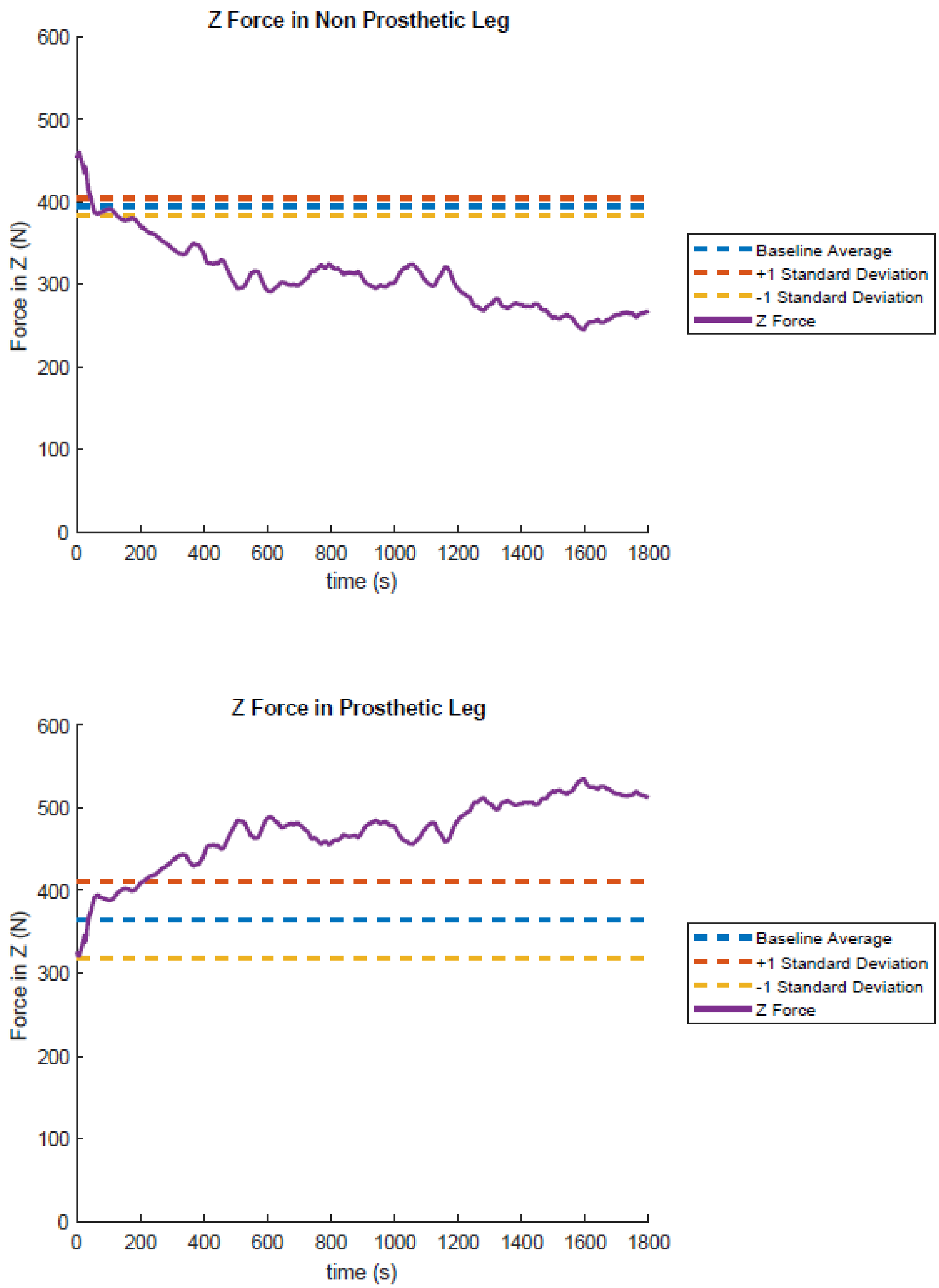
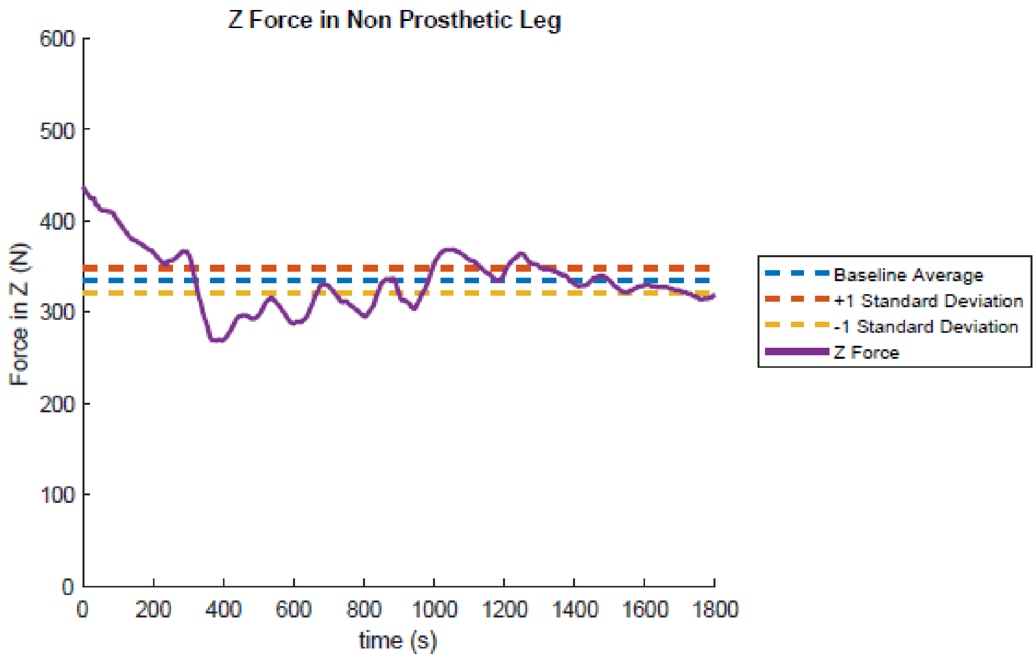


Figure 3.04: Force in the Z direction during prosthesis trial, compared to the baseline average for subject 3. The force in the Z direction does not appear to stabilize within the standard deviation of the baseline trials. This suggests a change in standing weight distribution caused by the introduced prosthesis.



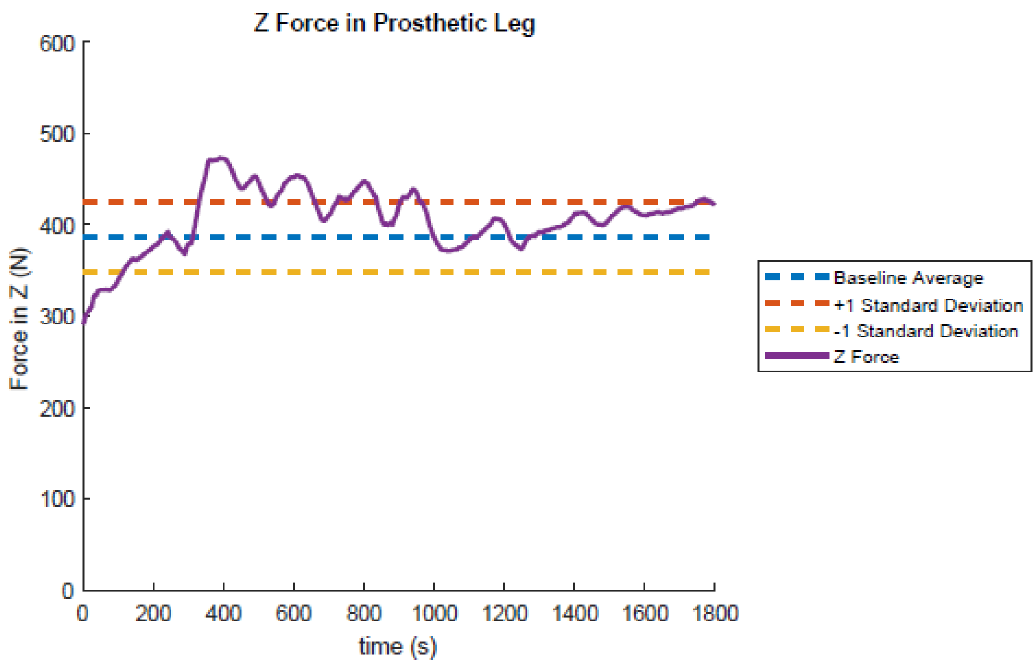
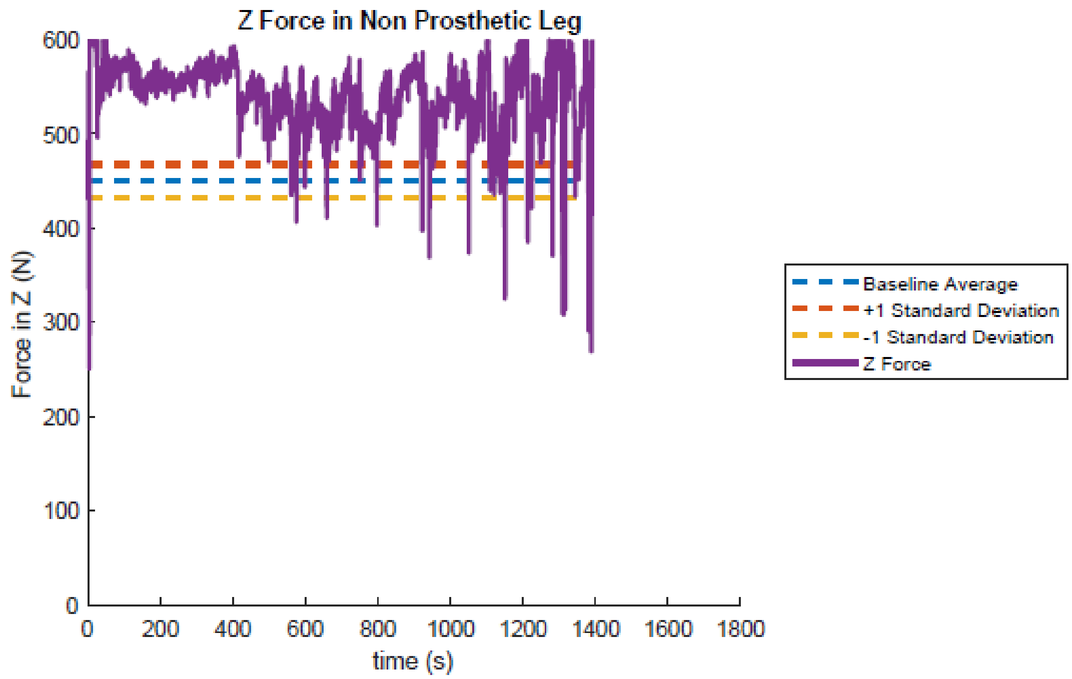


Figure 3.05: Force in the Z direction during prosthesis trial, compared to the baseline average for subject 4. The force in the Z direction does not appear to stabilize within the standard deviation of the baseline trials. This suggests a change in standing weight distribution caused by the introduced prosthesis.



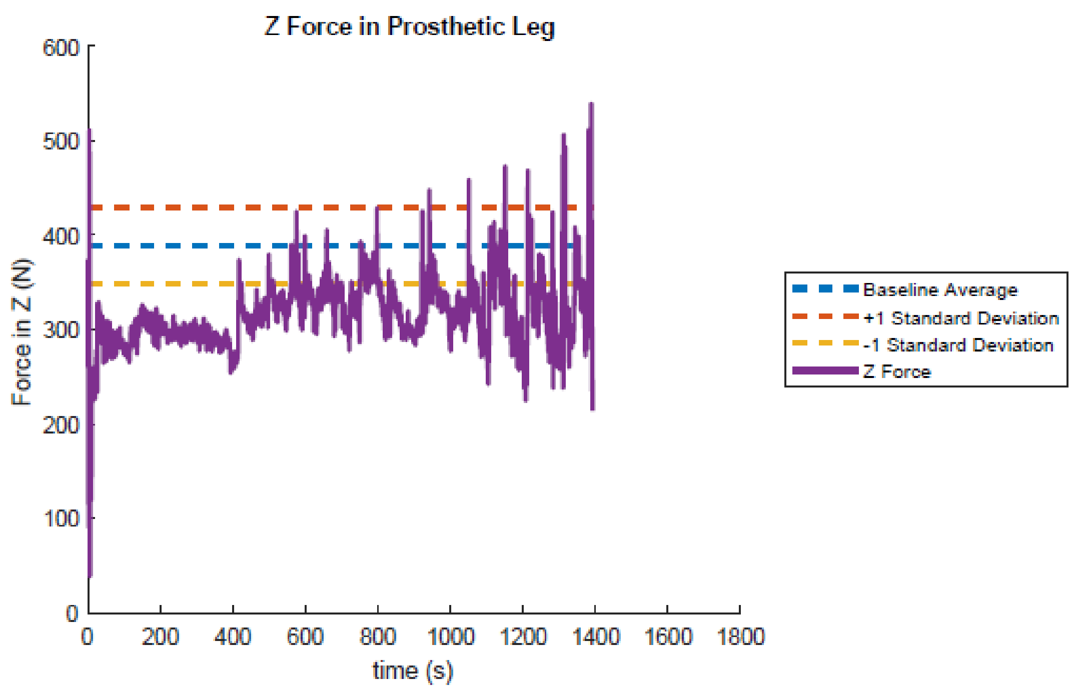
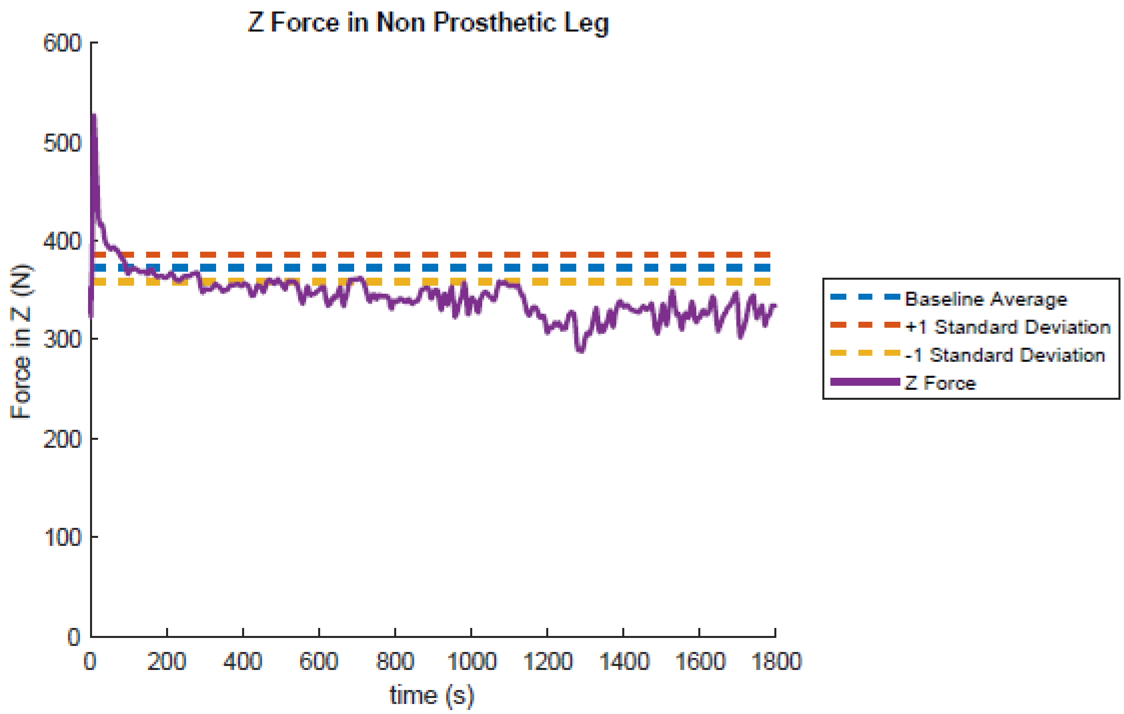


Figure 3.06: Force in the Z direction during prosthesis trial, compared to the baseline average for subject 5. The force in the Z direction does not appear to stabilize within the standard deviation of the baseline trials. This suggests a change in standing weight distribution caused by the introduced prosthesis.



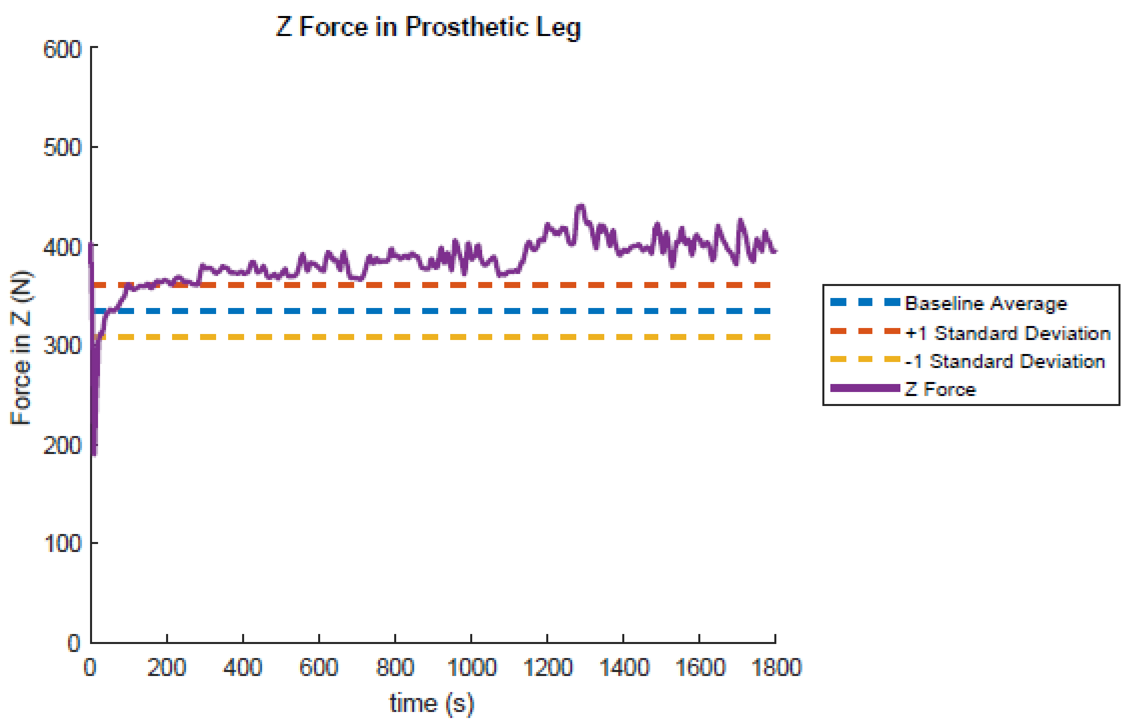


Figure 3.07: Force in the Z direction during prosthesis trial, compared to the baseline average for subject 6. The force in the Z direction does not appear to stabilize within the standard deviation of the baseline trials. This suggests a change in standing weight distribution caused by the introduced prosthesis.

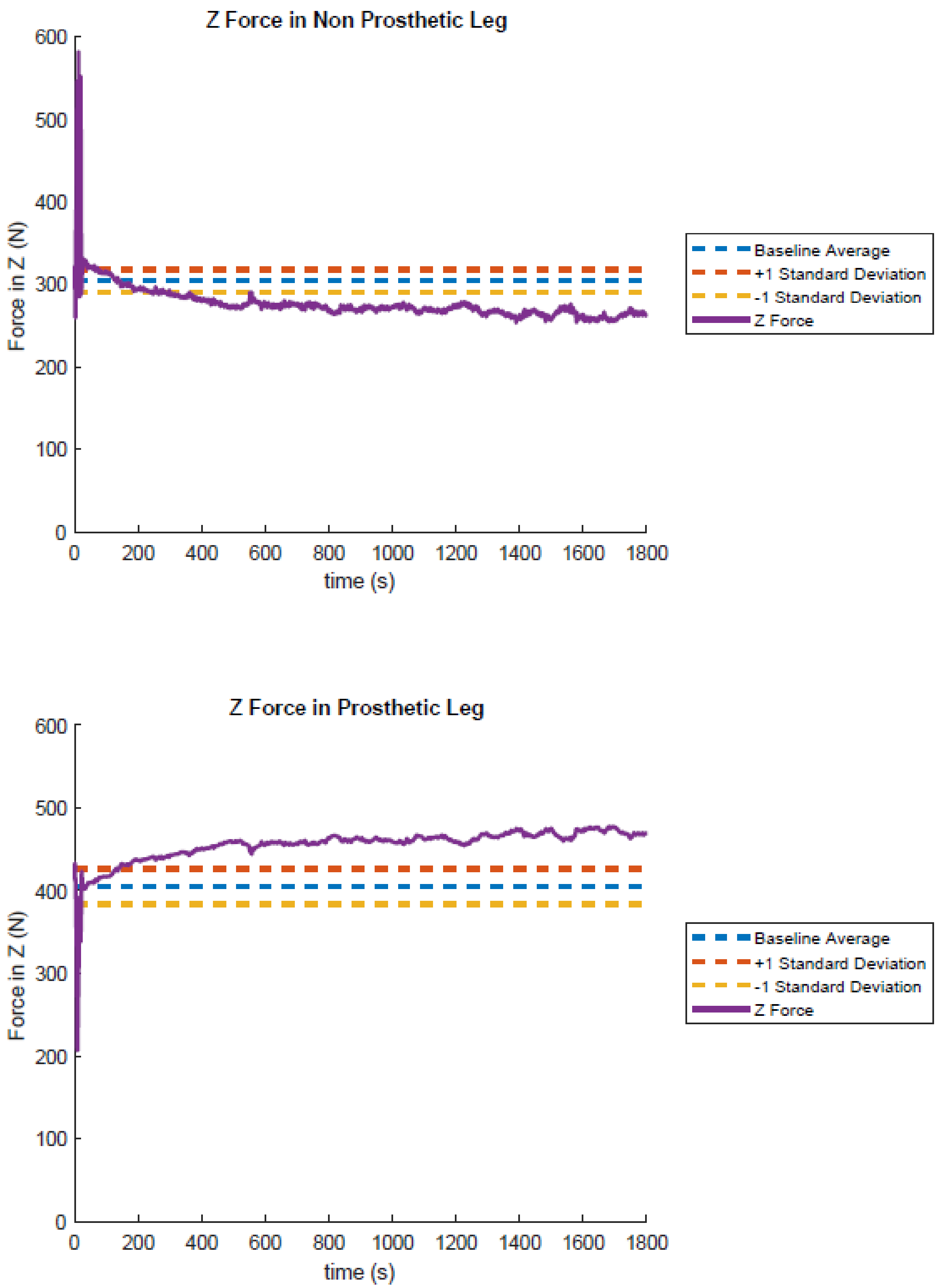
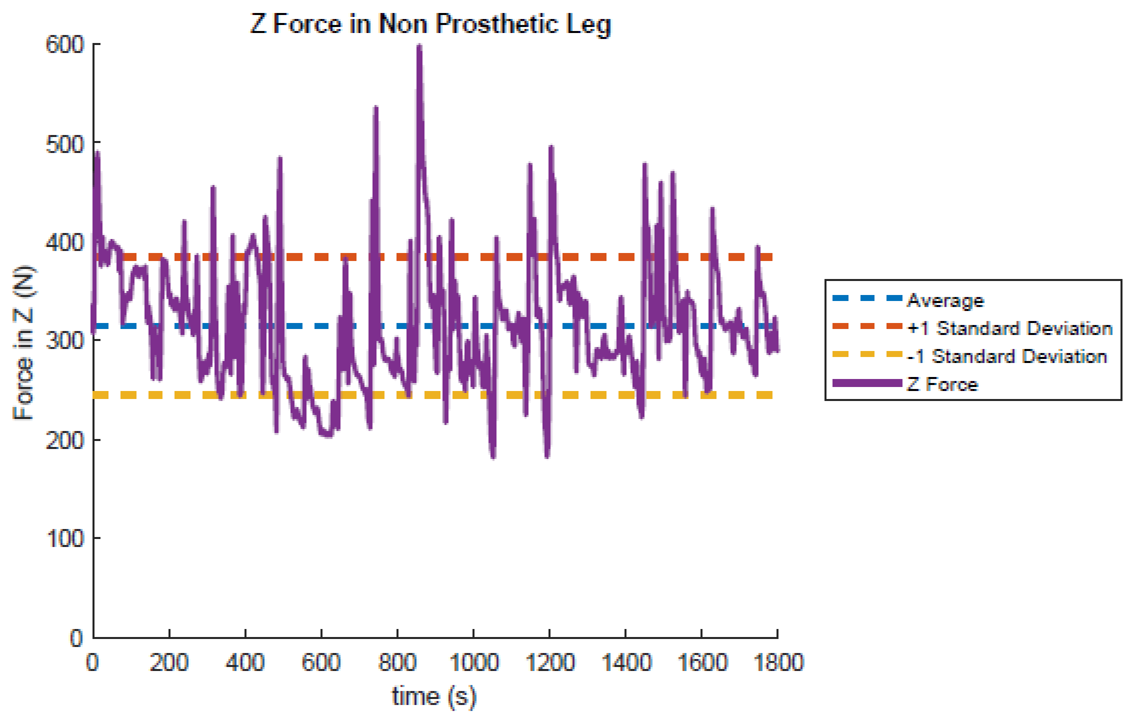


Figure 3.08: Force in the Z direction during prosthesis trial, compared to the baseline average for subject 7. The force in the Z direction does not appear to stabilize within the standard deviation of the baseline trials. This suggests a change in standing weight distribution caused by the introduced prosthesis.

Vertical force stabilization. To determine how quickly subjects adapted to the introduced prosthesis, the force in the Z direction was plotted against the average and standard distribution to determine how quickly the force in the Z direction stabilized between the standard deviations. This is shown in figures 3.09-3.15 below. All subjects stabilized to within one standard deviation over the course of the trial. All subjects also reached the stabilized region within the first 200 seconds of the trial. This means that the learning period for using the introduced prosthesis was within the first 200 seconds of the trial, at least for achieving a momentary steady state in these standard deviations.



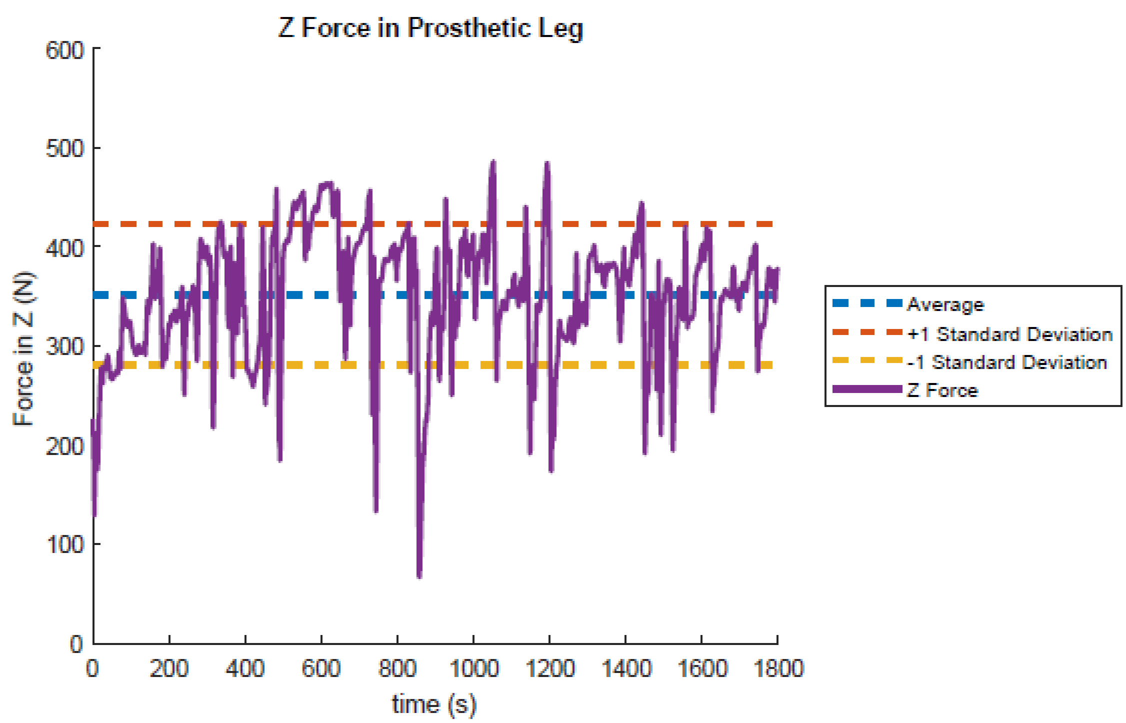
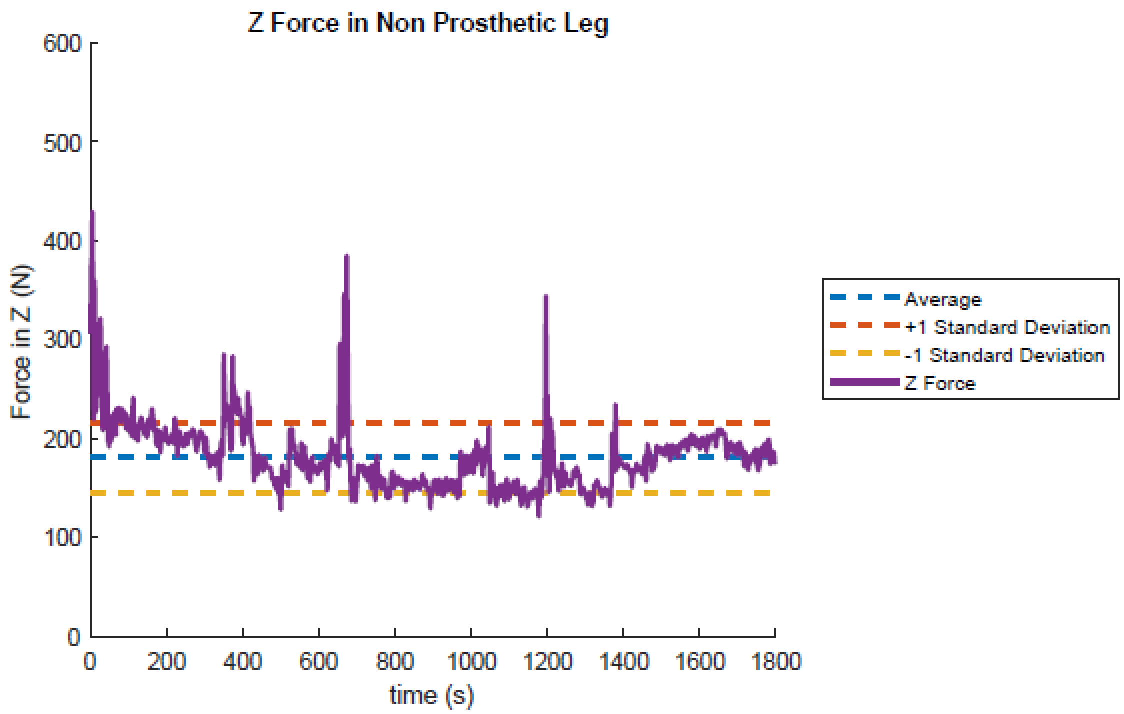


Figure 3.09: Force in the Z direction with the average for subject 1. The force in the Z direction returns stabilizes within one standard deviation over the course of the trial.



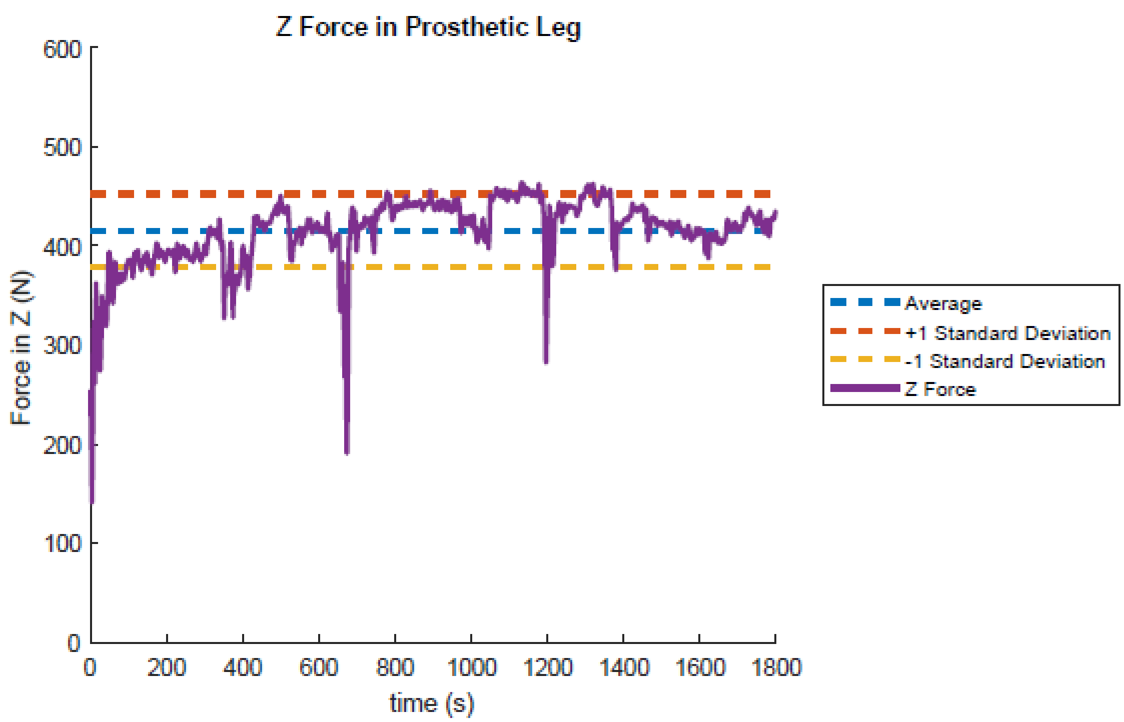
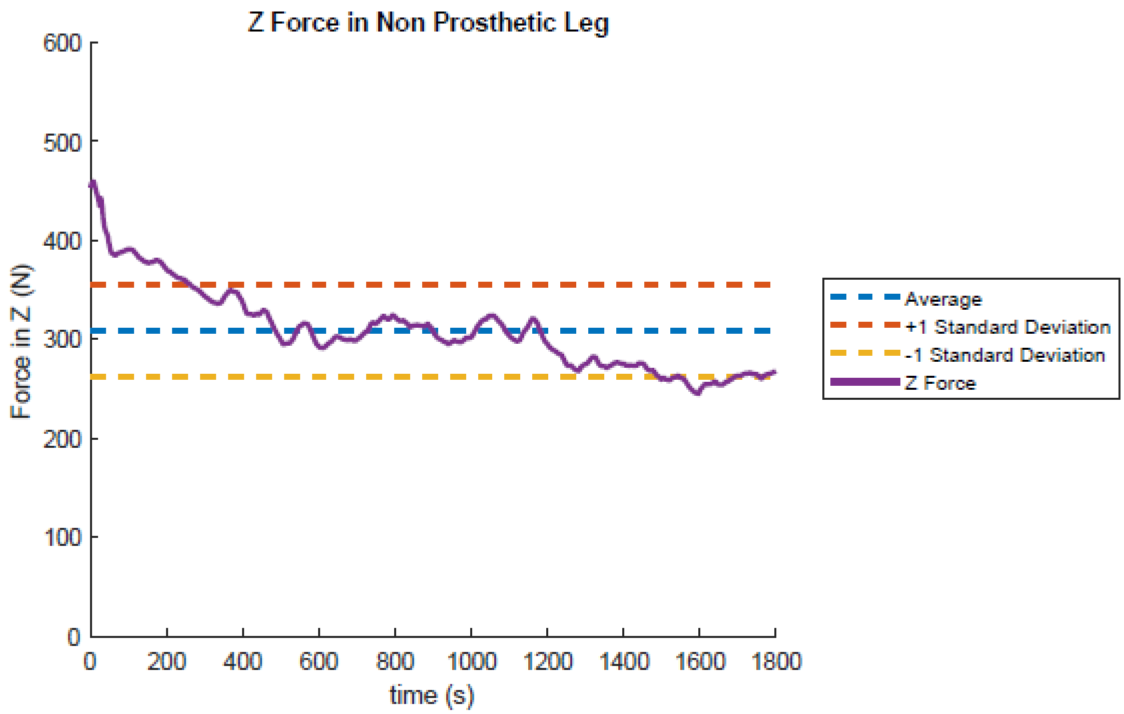


Figure 3.10: Force in the Z direction with the average for subject 2. The force in the Z direction returns stabilizes within one standard deviation over the course of the trial.



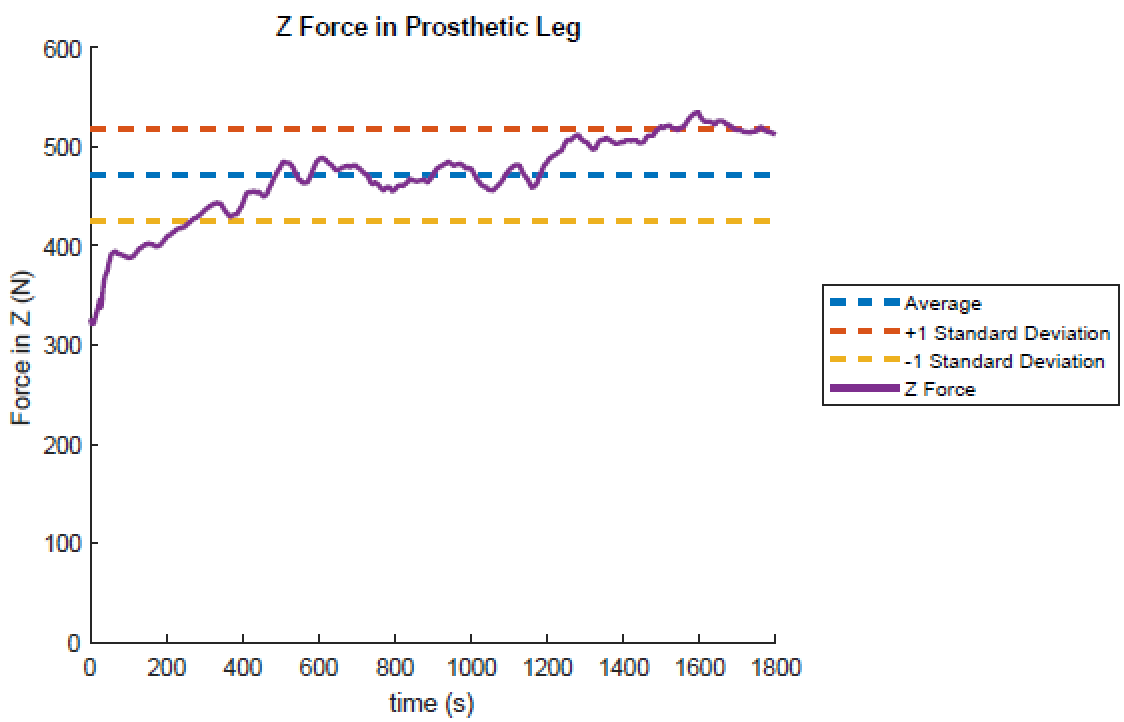
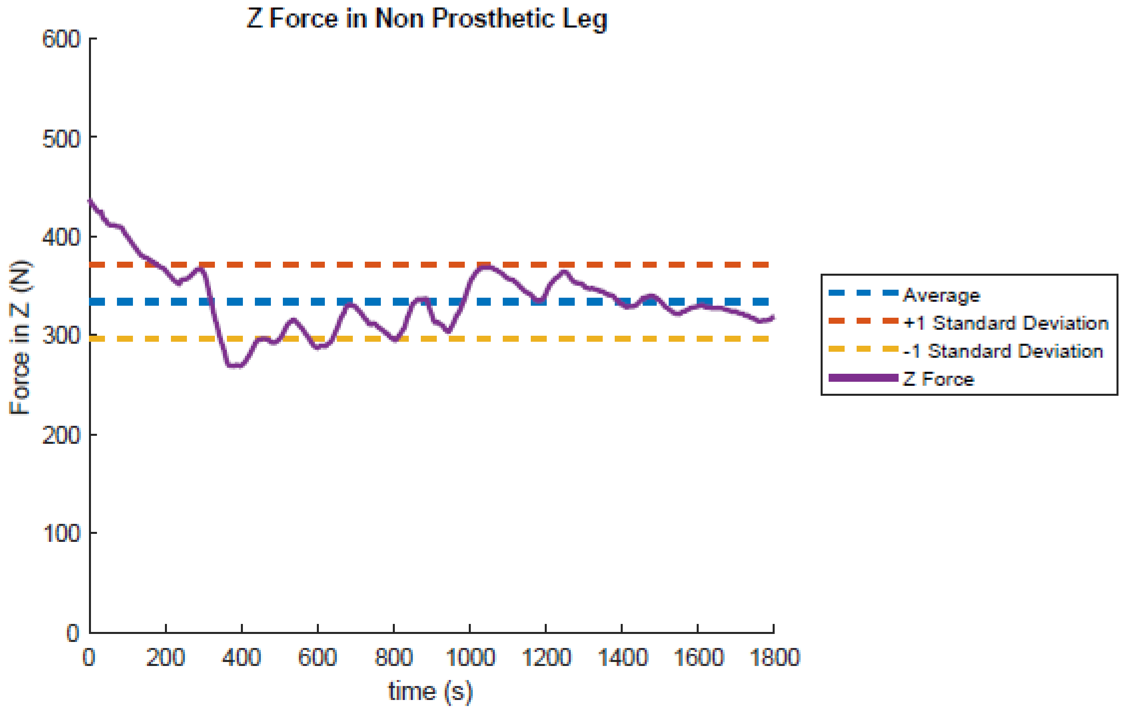


Figure 3.11: Force in the Z direction with the average for subject 3. The force in the Z direction returns stabilizes within one standard deviation over the course of the trial.



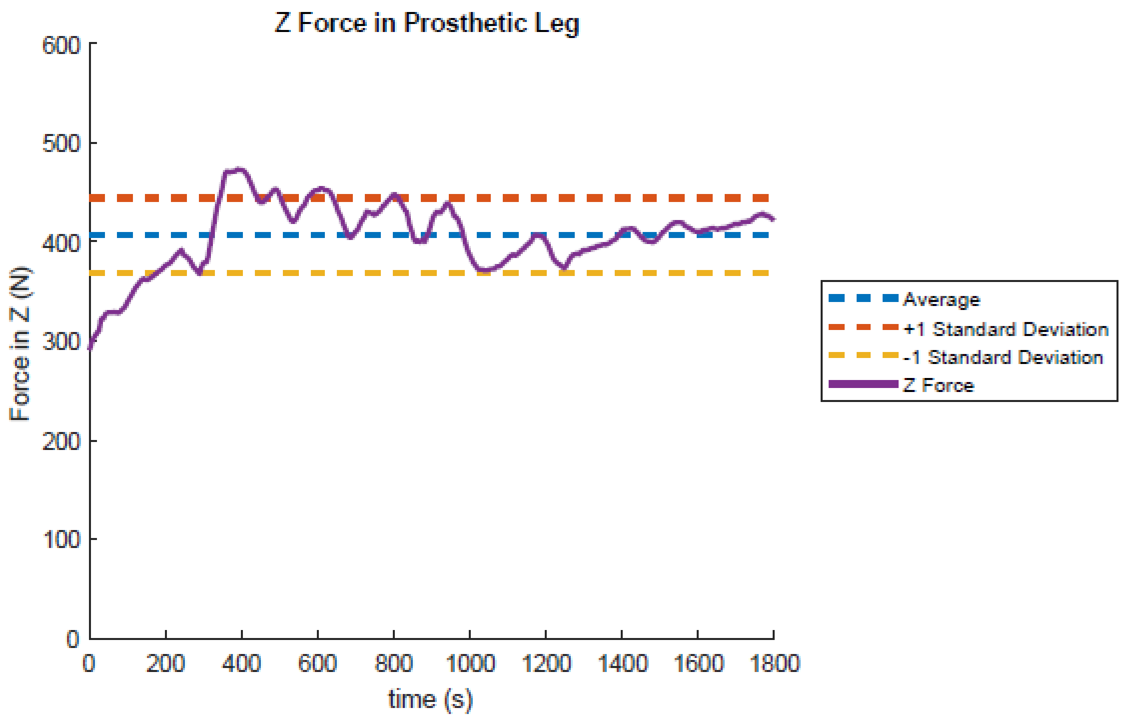
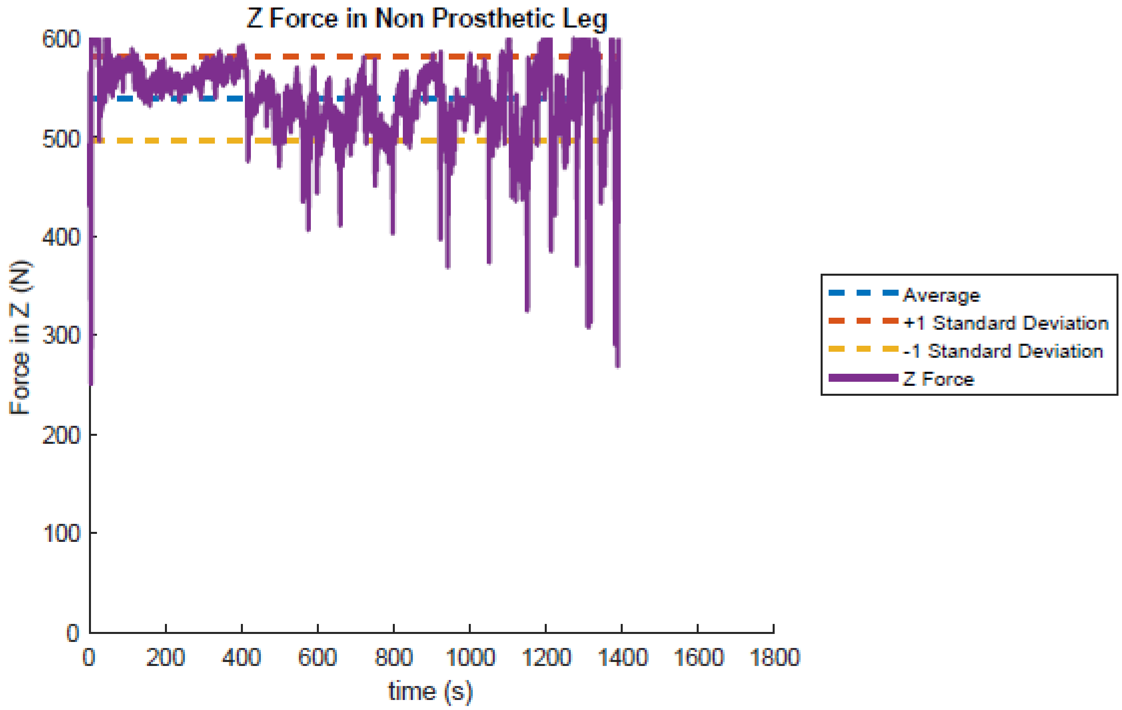


Figure 3.12: Force in the Z direction with the average for subject 4. The force in the Z direction returns stabilizes within one standard deviation over the course of the trial.



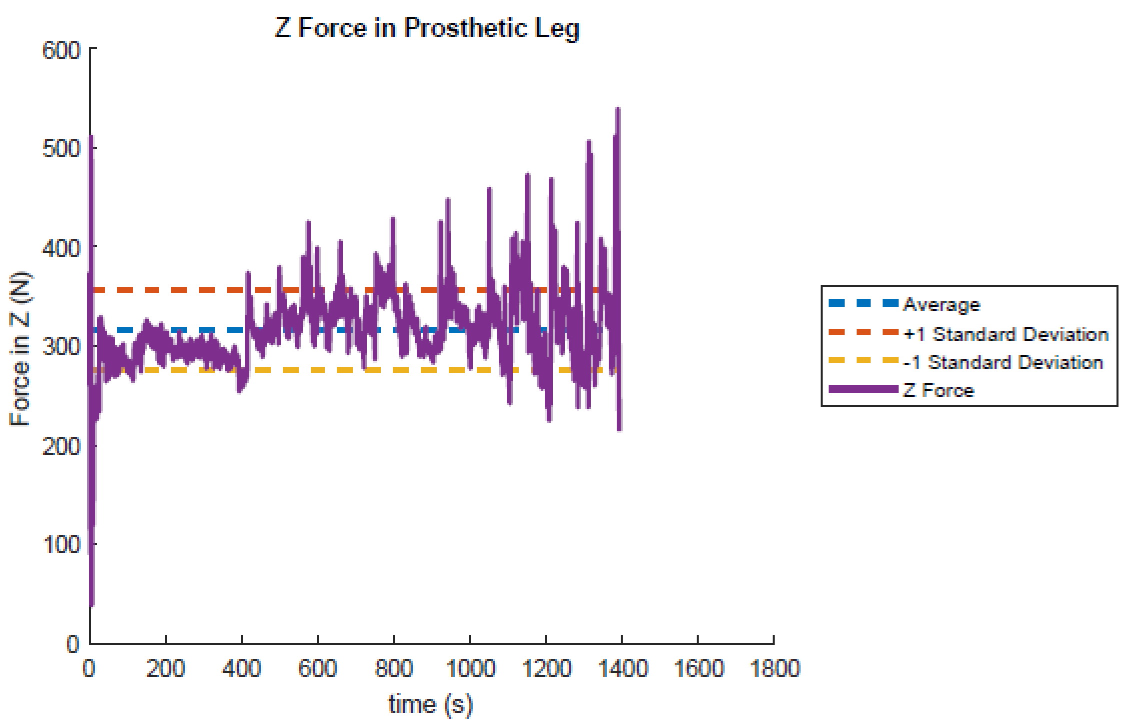


Figure 3.13: Force in the Z direction with the average for subject 5. The force in the Z direction returns stabilizes within one standard deviation over the course of the trial.

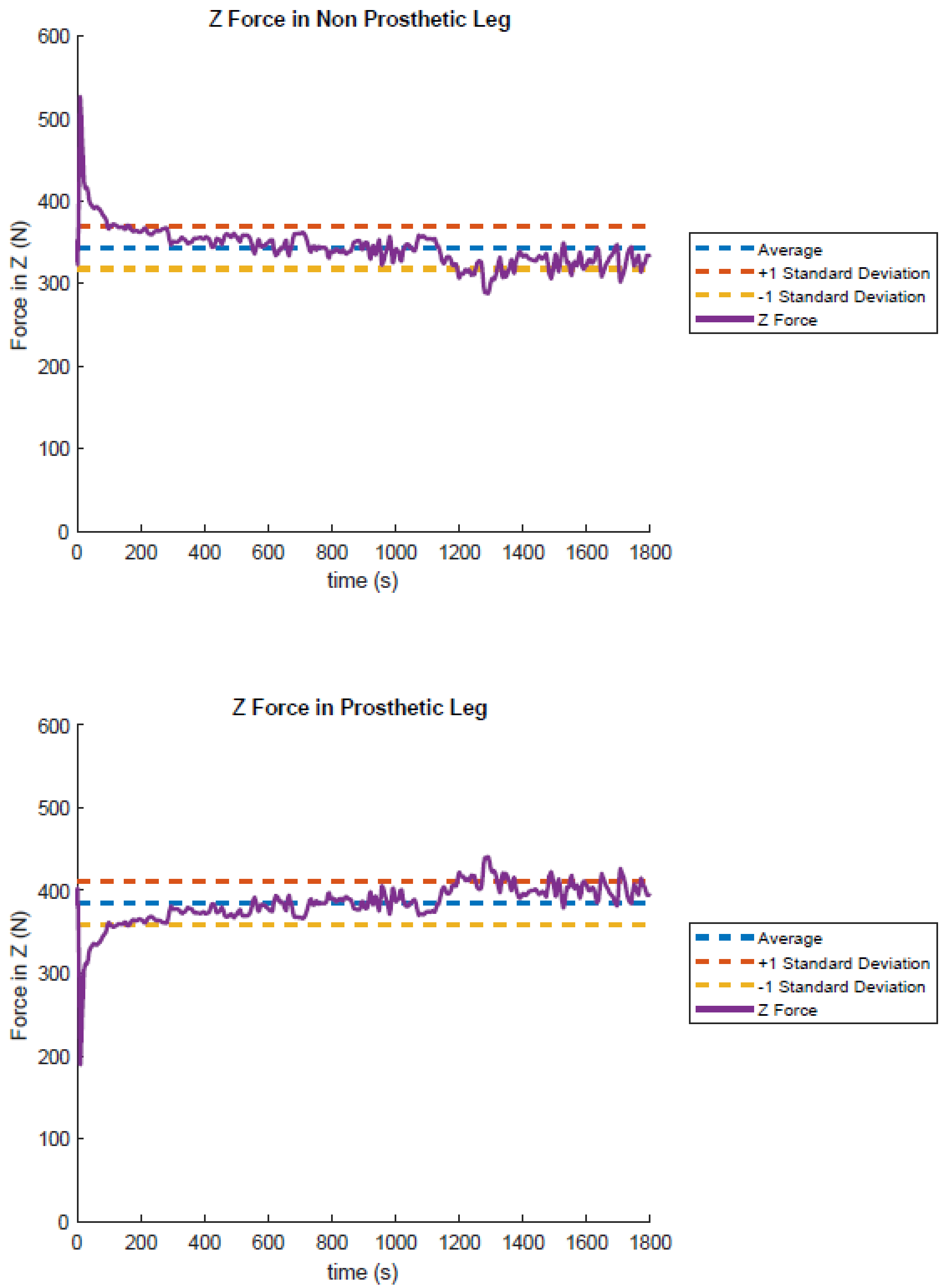
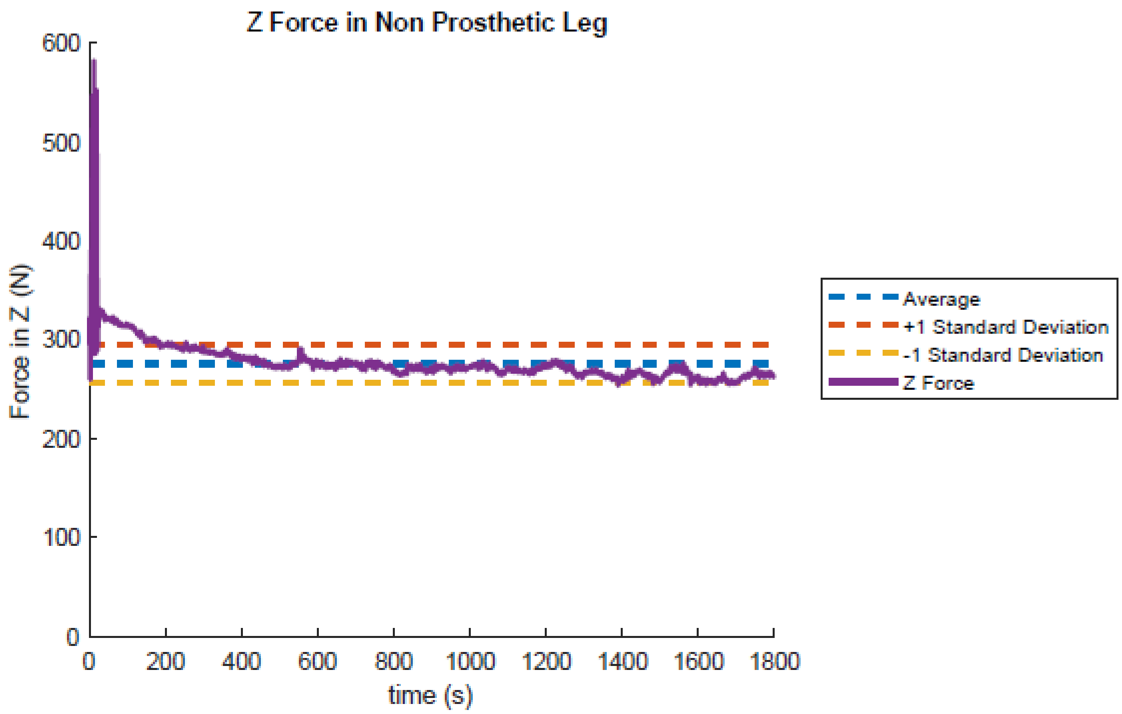


Figure 3.14: Force in the Z direction with the average for subject 6. The force in the Z direction returns stabilizes within one standard deviation over the course of the trial.



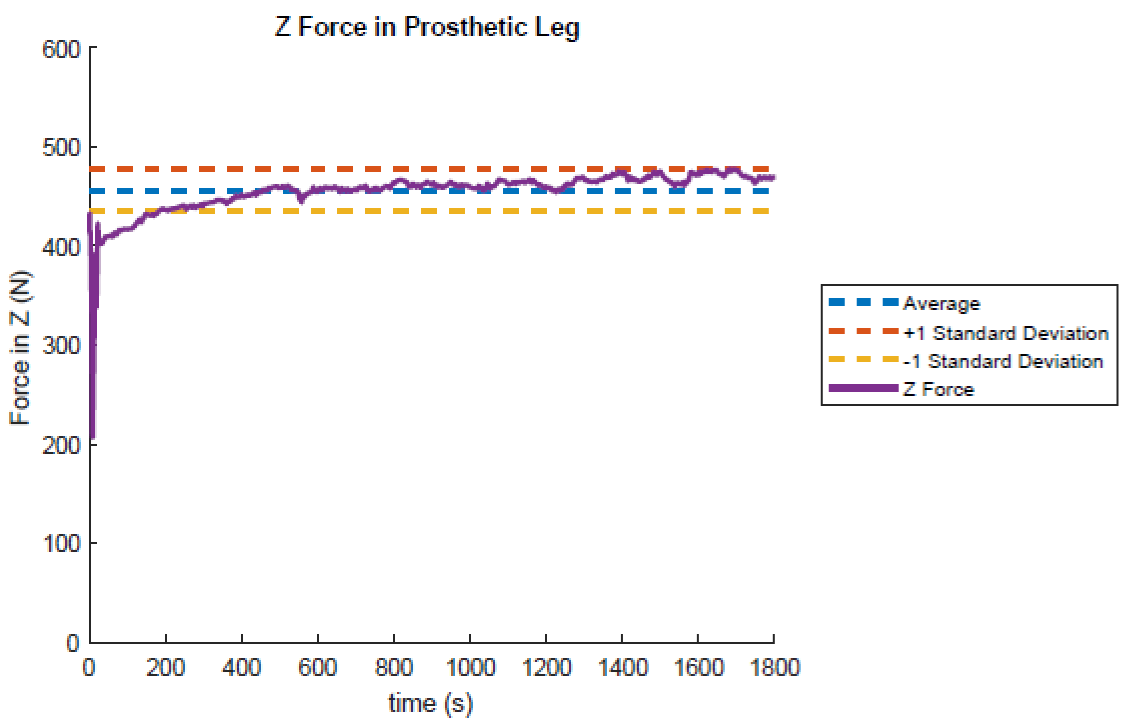
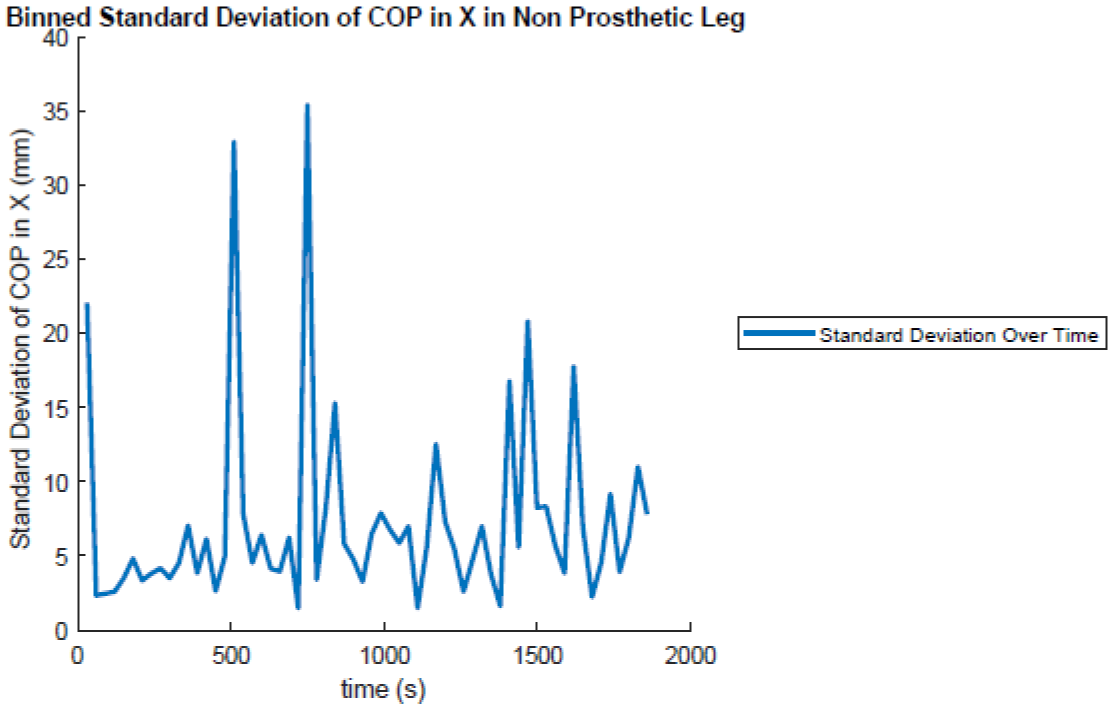


Figure 3.15: Force in the Z direction with the average for subject 7. The force in the Z direction returns stabilizes within one standard deviation over the course of the trial.

3.2 Center of Pressure variability over time

The variability of the CoP over time was measured by the change in standard deviation; figures 3.16 through 3.22 show the change in standard deviation over time for X and figures 3.23-3.29 show the change in the standard deviation over time for Y. The standard deviations were calculated over 30 second intervals over the course of the trial. In all subjects, the standard deviation in both the X and Y directions decreased from the start to the end of the trial. For all subjects, the standard deviations in the Y direction leveled off (on average), suggesting that the subjects were stable in balancing in that direction. In the X direction, only subjects 3 and 7 showed signs of stabilization, where the other subjects were still standard deviations were still fluctuating. Combined this suggests that the subjects were more stable in the YZ plane, but not as stable in the XZ plane.



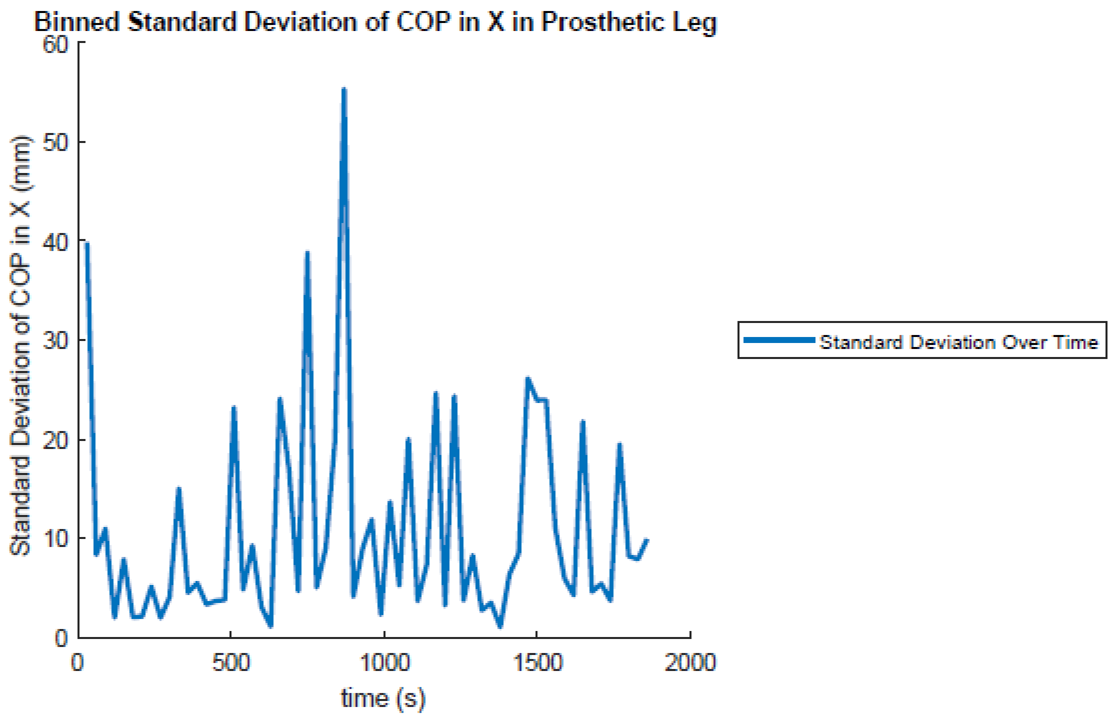
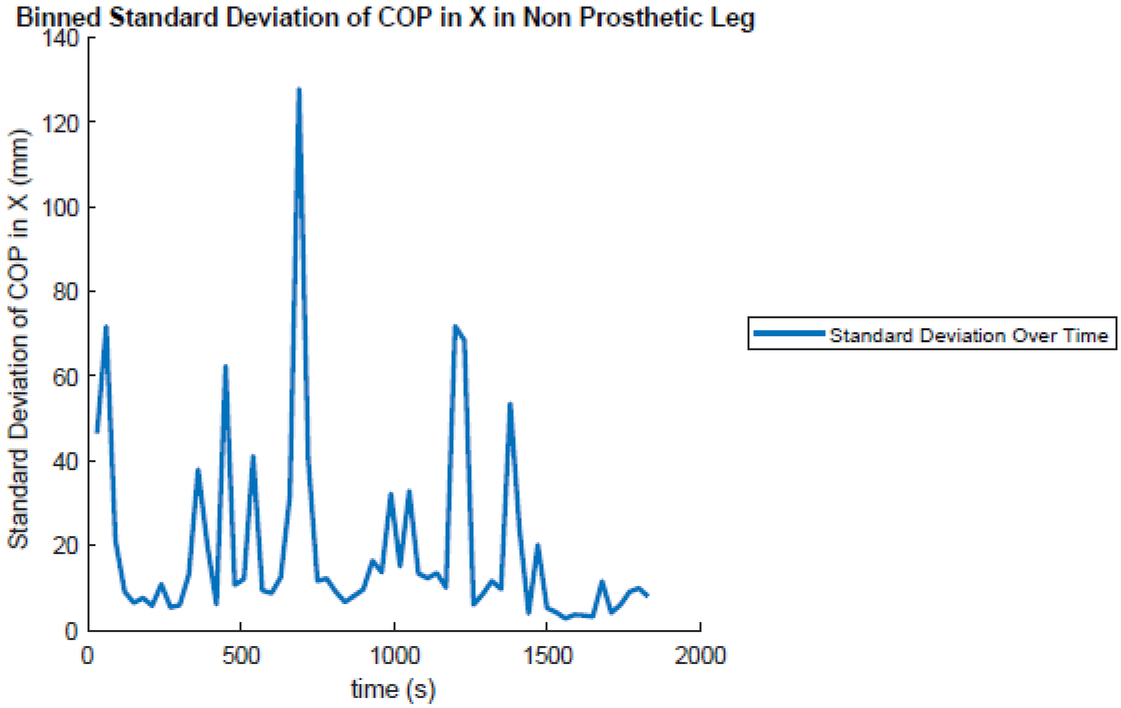


Figure 3.16: Standard deviation of COP X over time for subject 1. While having some very high standard deviations for certain intervals in the middle of the trial, the standard deviation decreased from the start to finish.



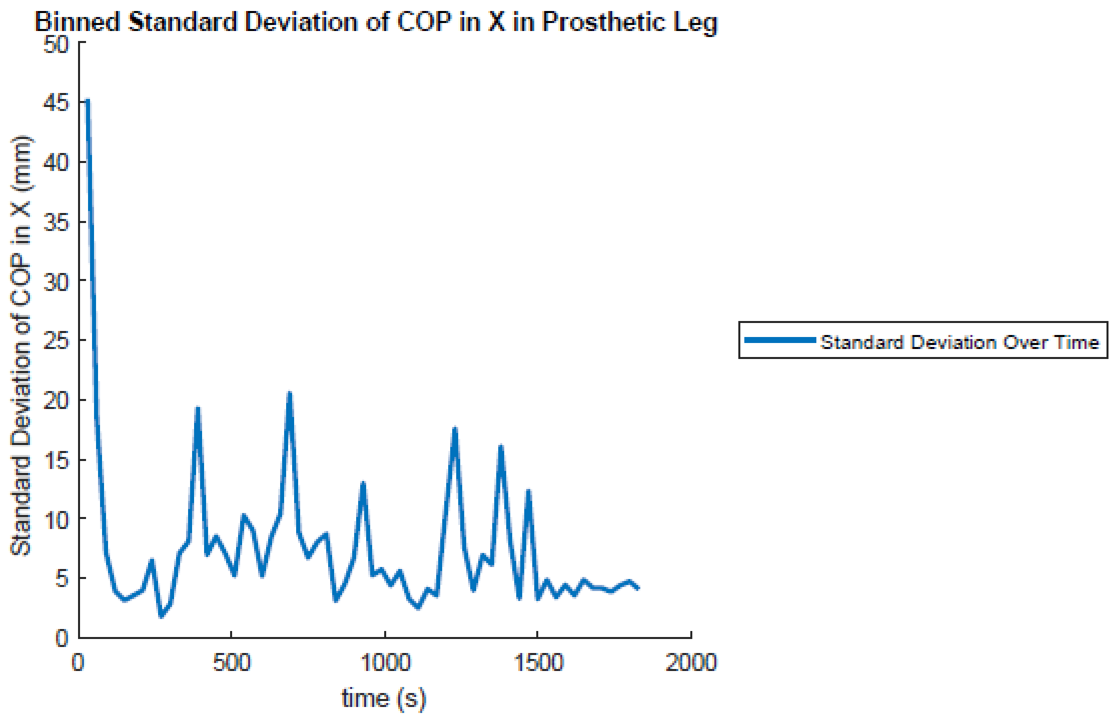
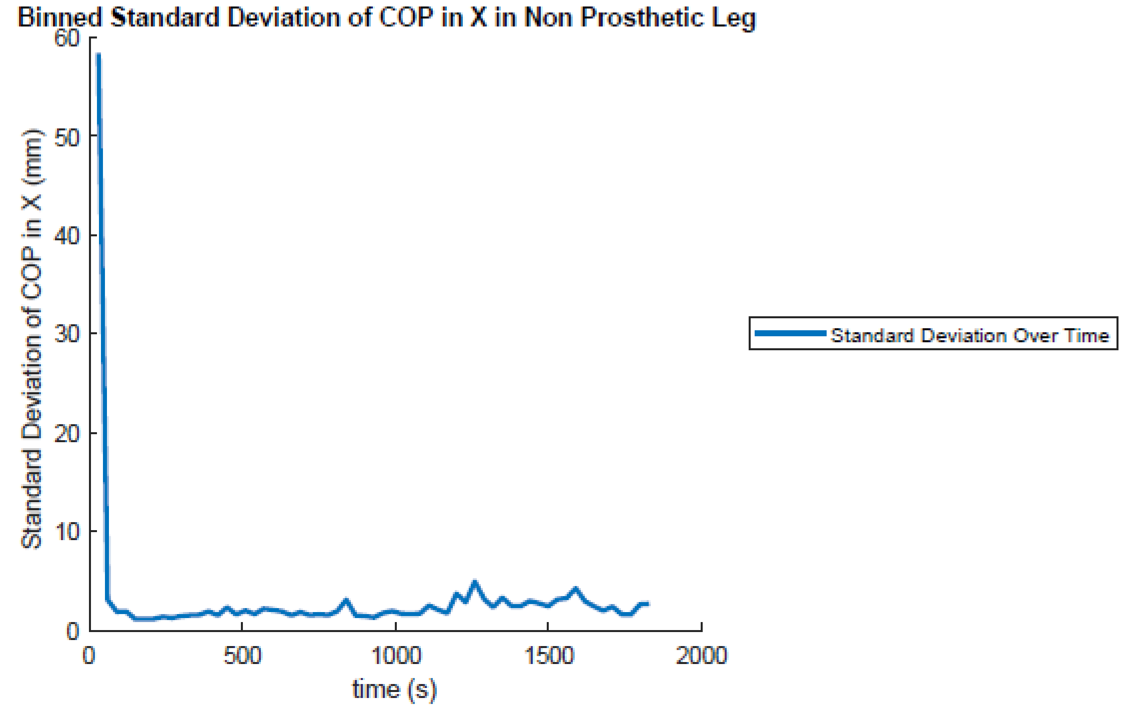


Figure 3.17: Standard deviation of COP X over time for subject 2. While having some high standard deviation for certain intervals, the standard deviation decreased from the start of the trial to the end of the trial.



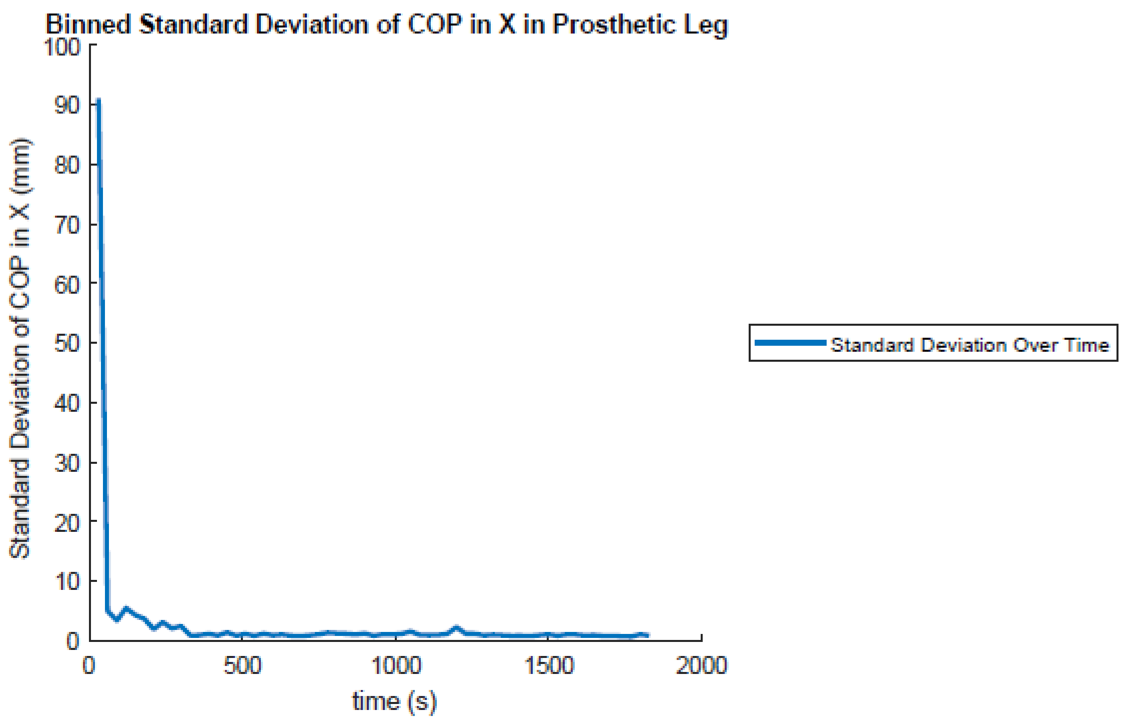


Figure 3.18: Standard deviation of COP X over time for subject 3. The standard deviation decreased from the start of the trial to the end of the trial.

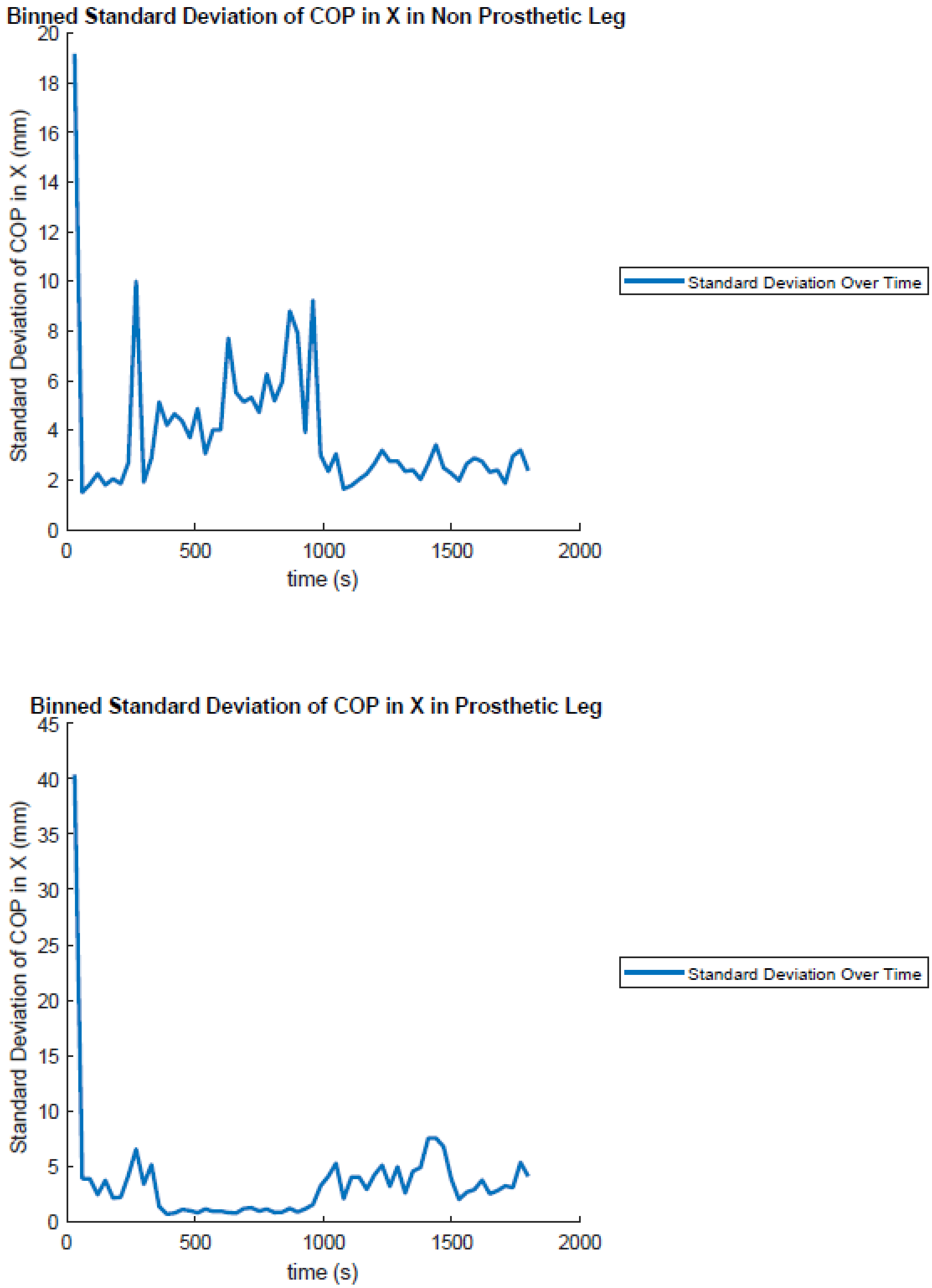
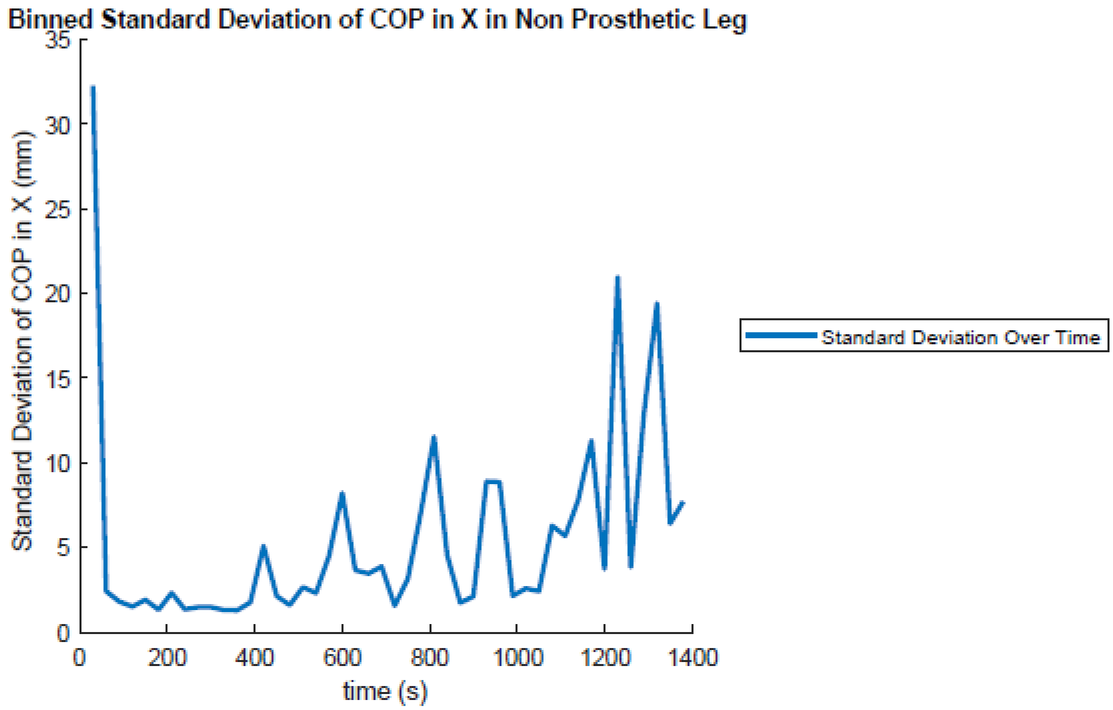


Figure 3.19: Standard deviation of COP X over time for subject 4. The standard deviation decreased from the start of the trial to the end of the trial.



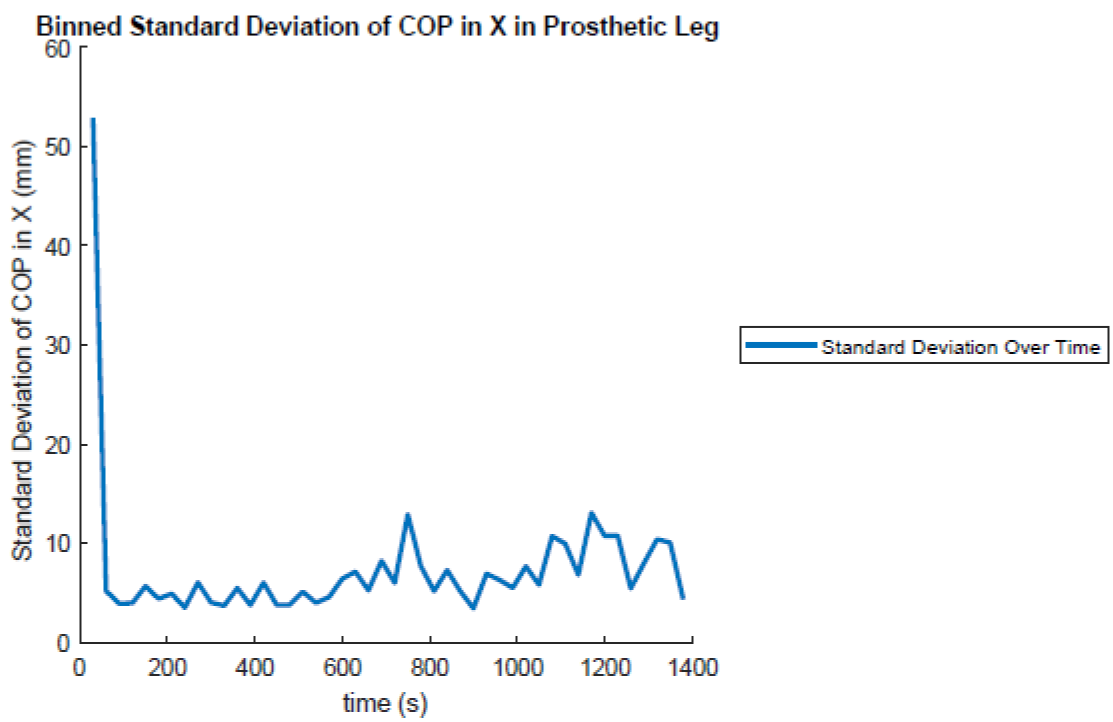
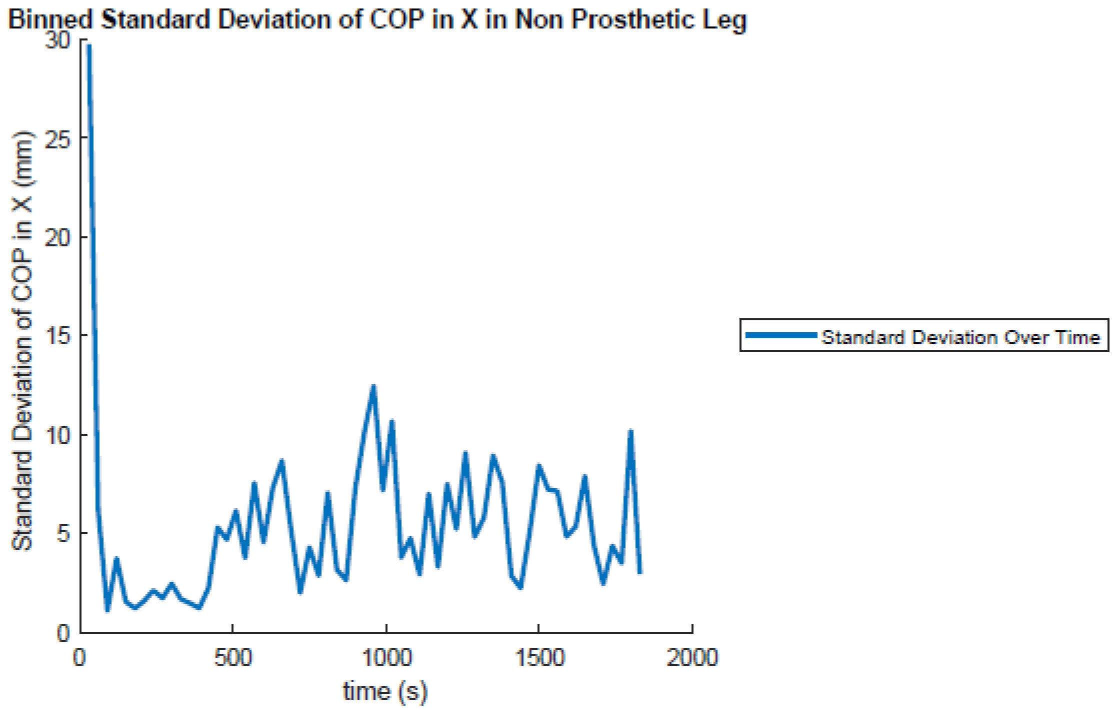


Figure 3.20: Standard deviation of COP X over time for subject 5. The standard deviation decreased from the start of the trial to the end of the trial.



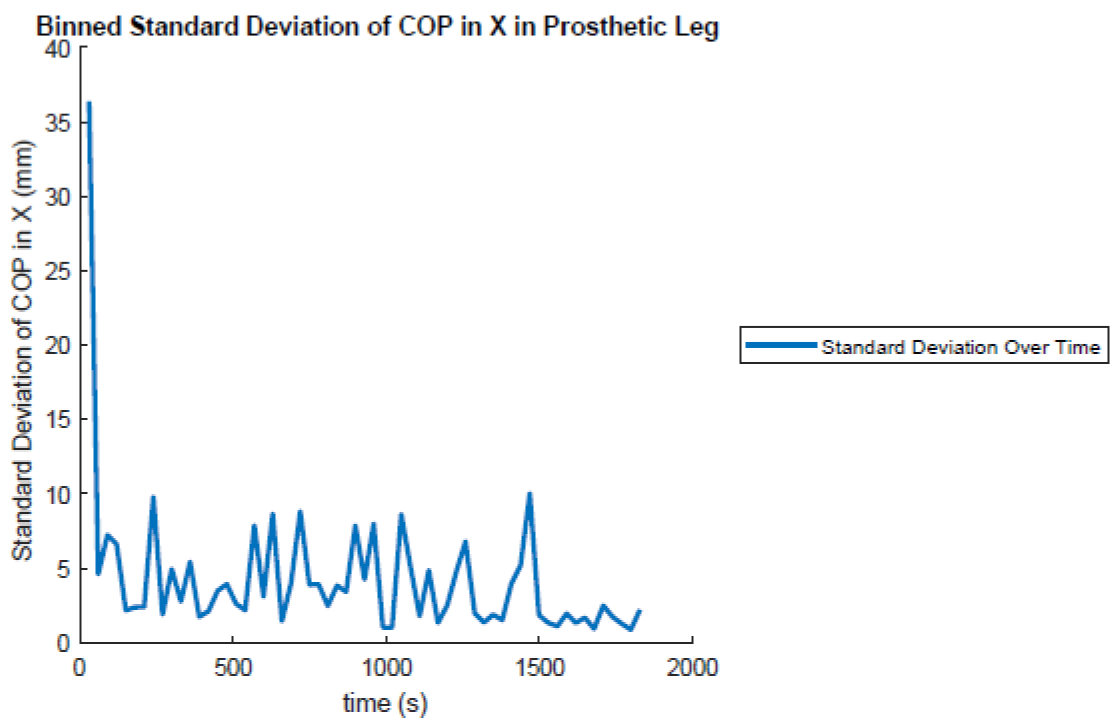
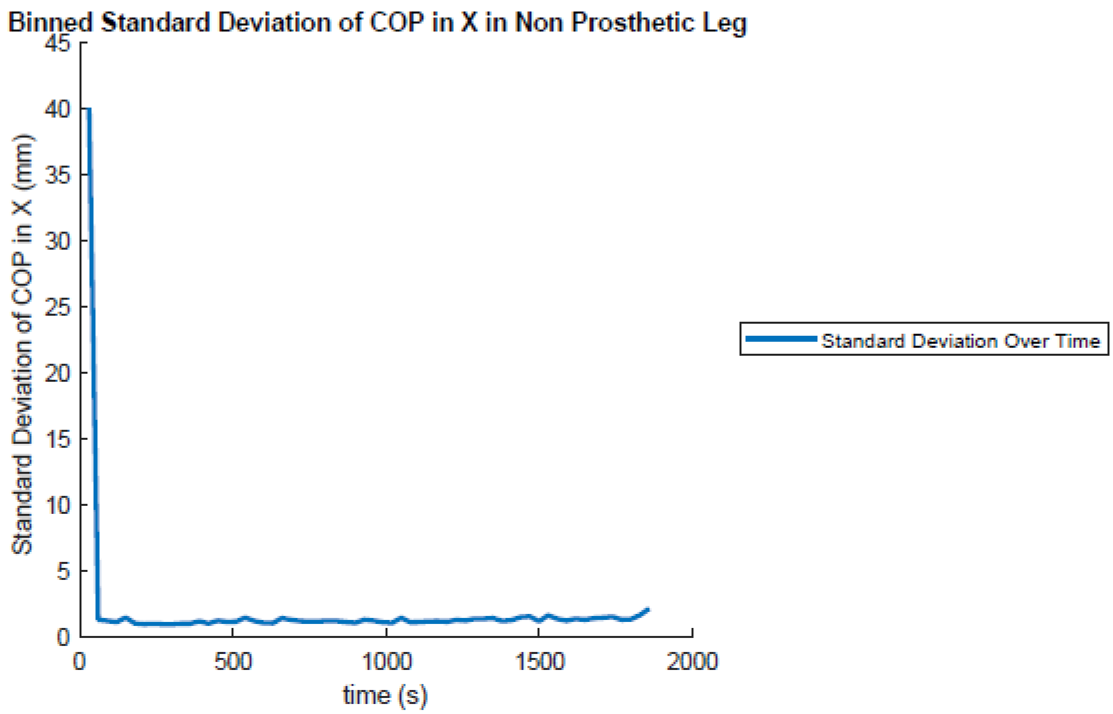


Figure 3.21: Standard deviation of COP X over time for subject 6. The standard deviation decreased from the start of the trial to the end of the trial.



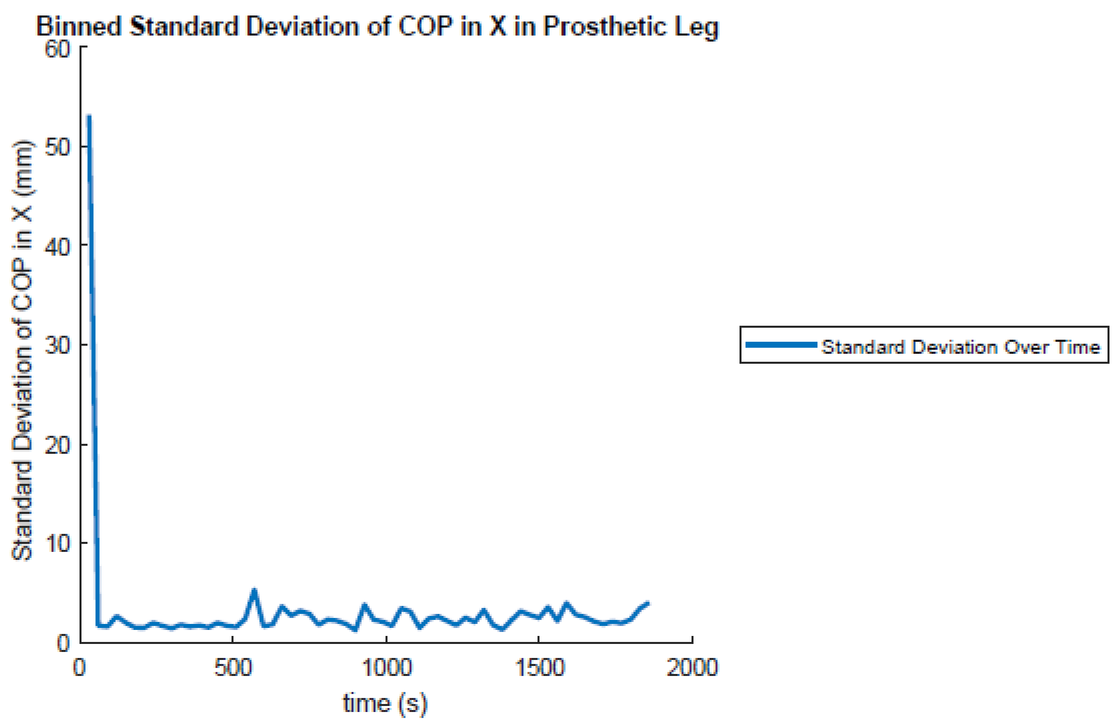
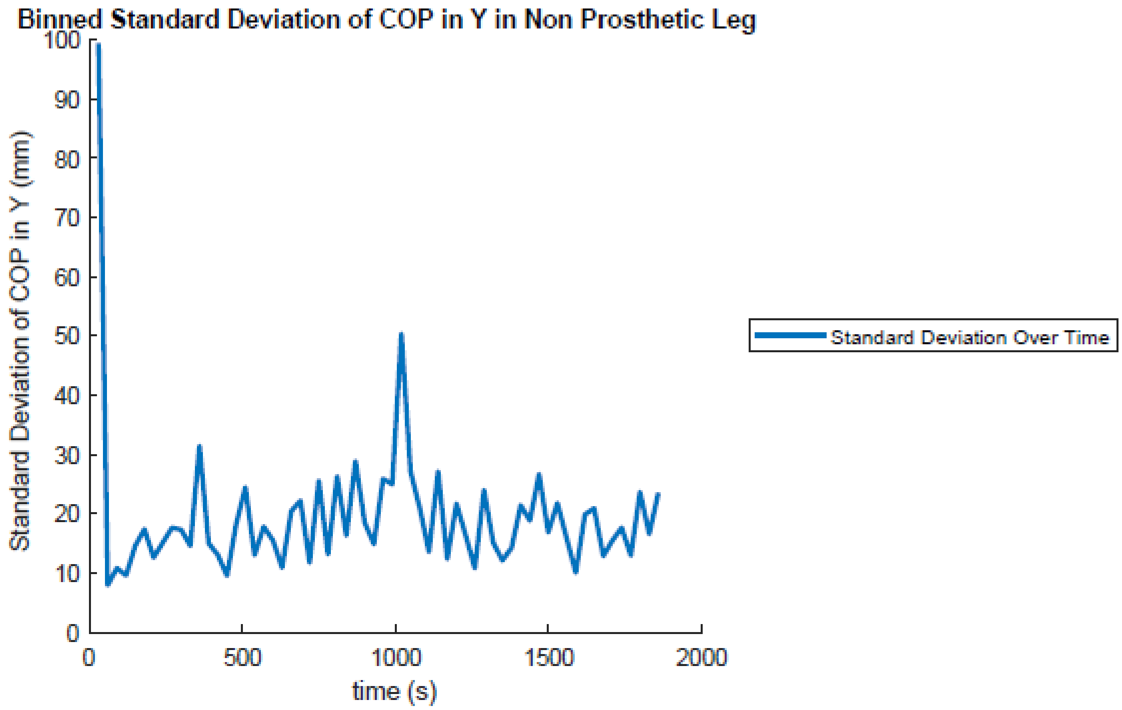


Figure 3.22: Standard deviation of COP X over time for subject 7. The standard deviation decreased from the start of the trial to the end of the trial.



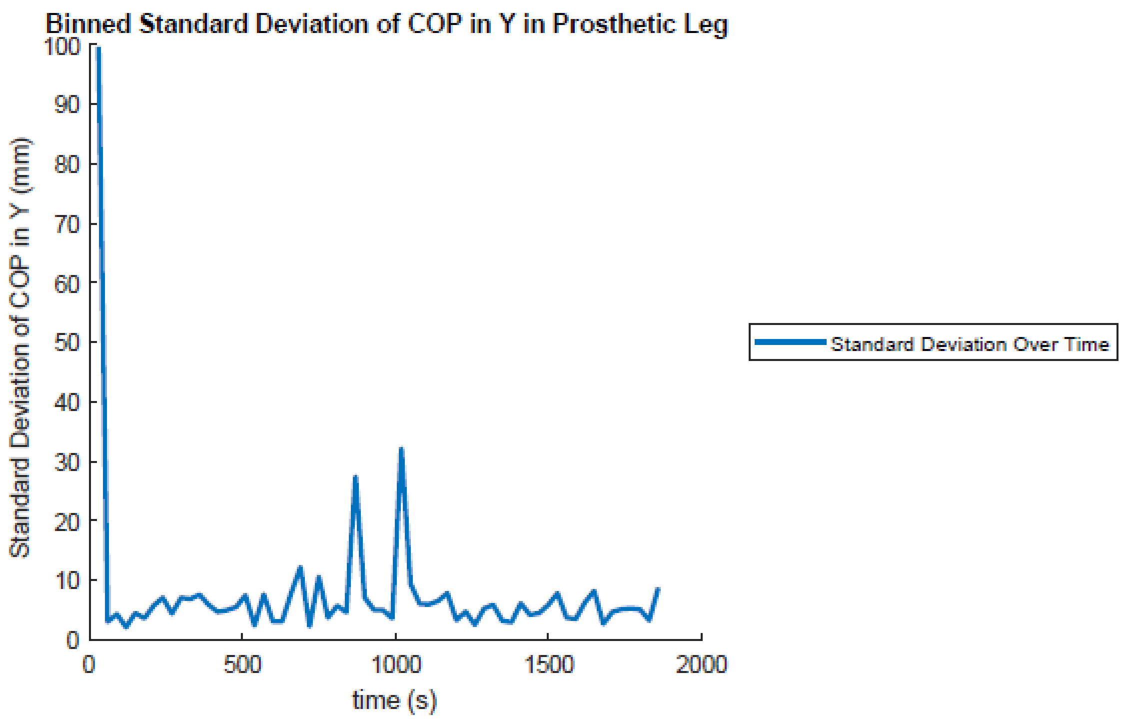


Figure 3.23: Standard deviation of COP Y over time for subject 1. The standard deviation decreased from the start of the trial to the end of the trial.

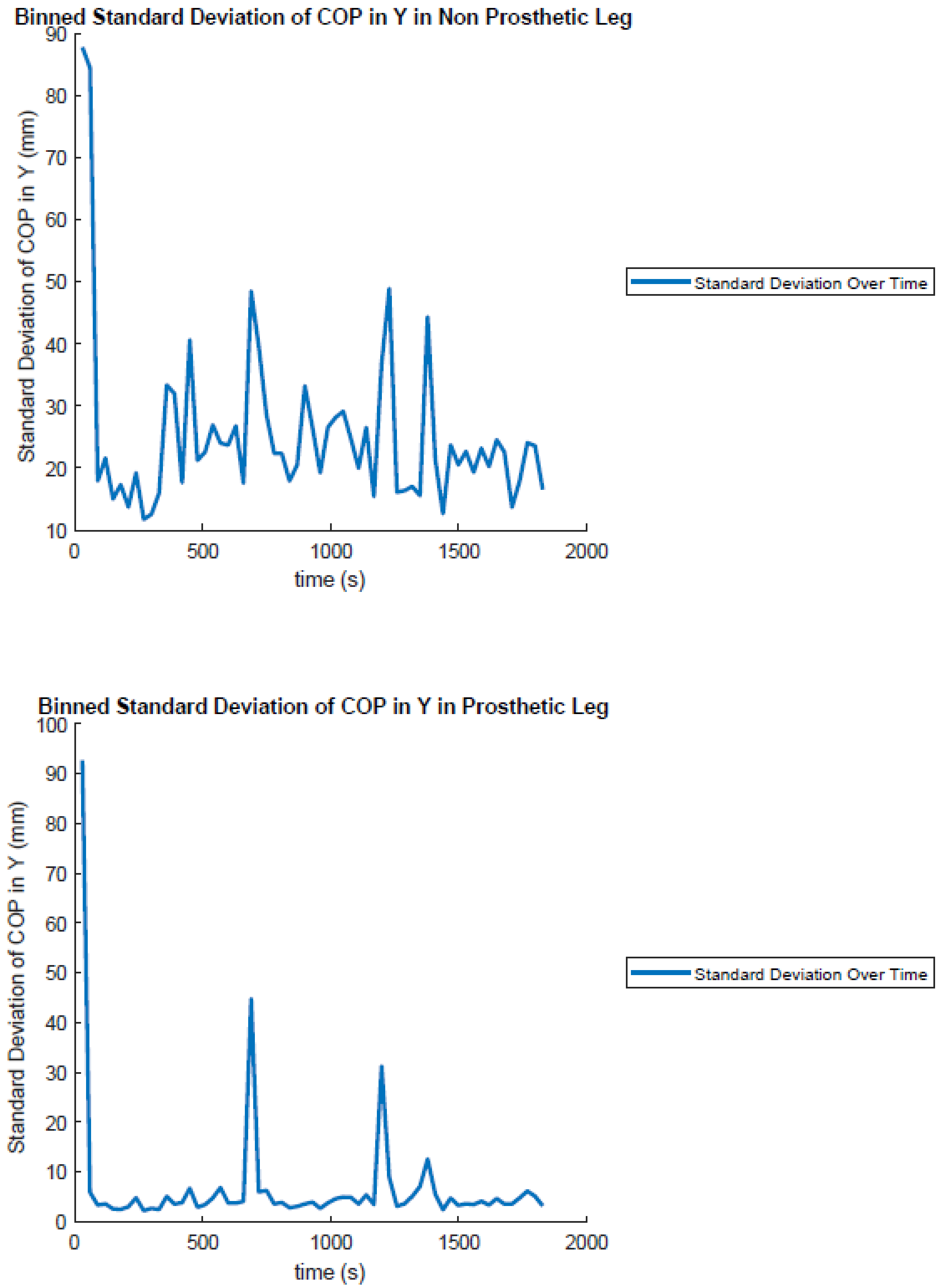
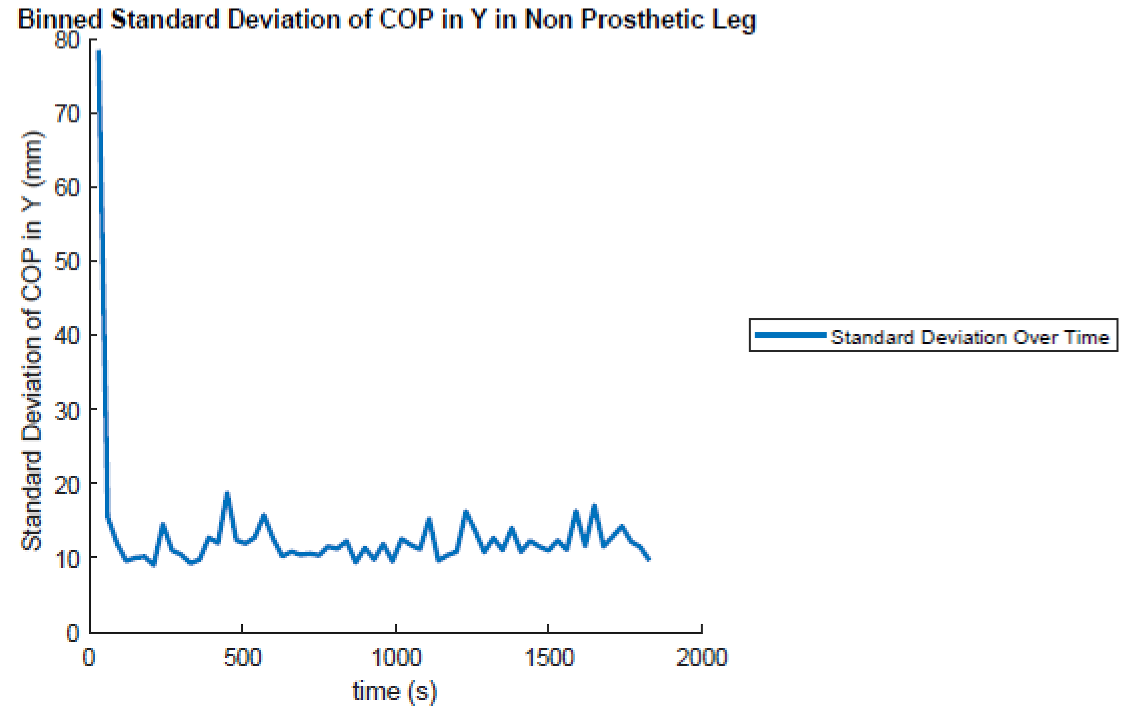


Figure 3.24: Standard deviation of COP Y over time for subject 2. The standard deviation decreased from the start of the trial to the end of the trial.



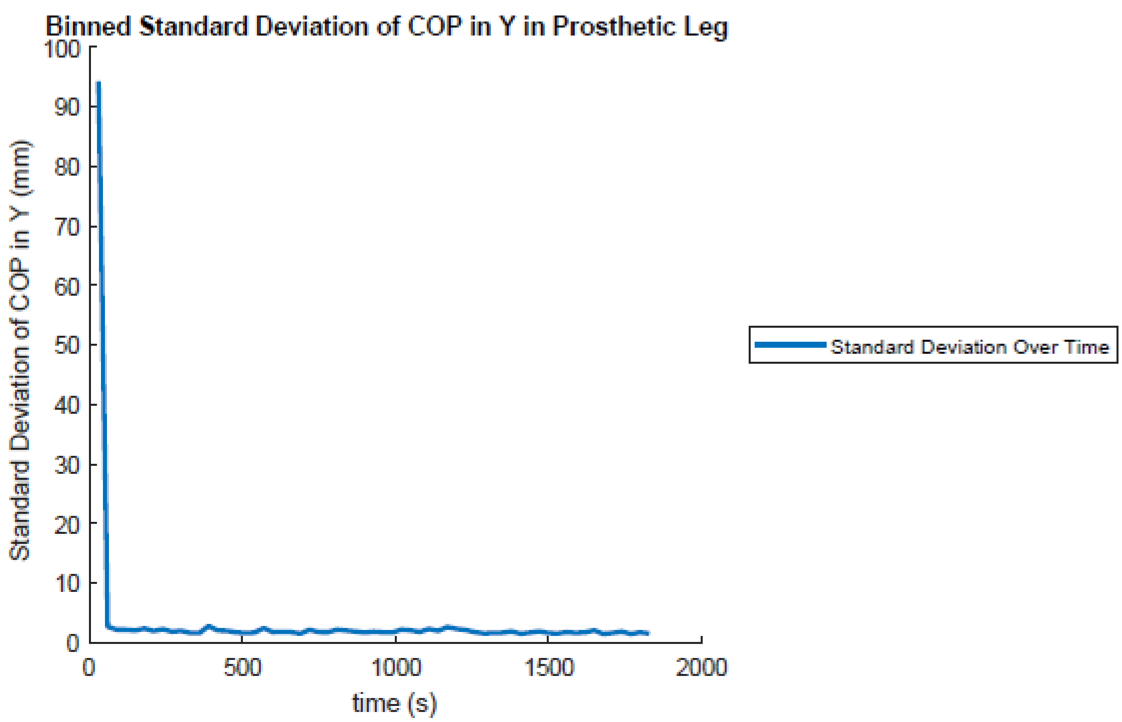
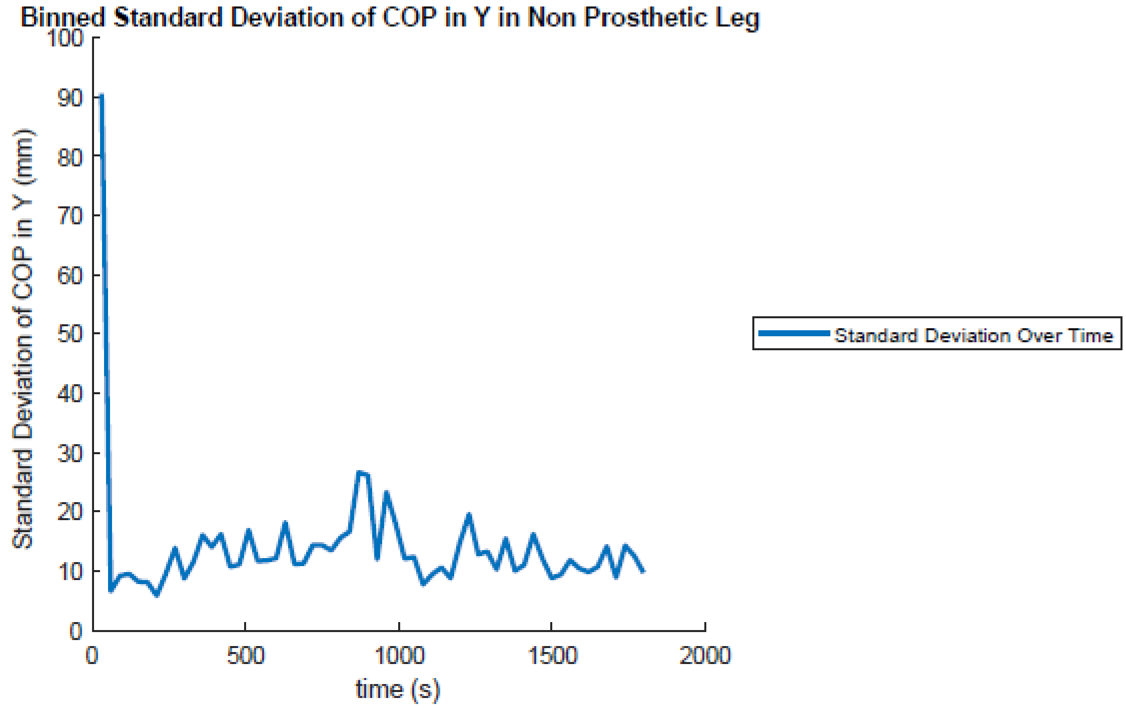


Figure 3.25: Standard deviation of COP Y over time for subject 3. The standard deviation decreased from the start of the trial to the end of the trial.



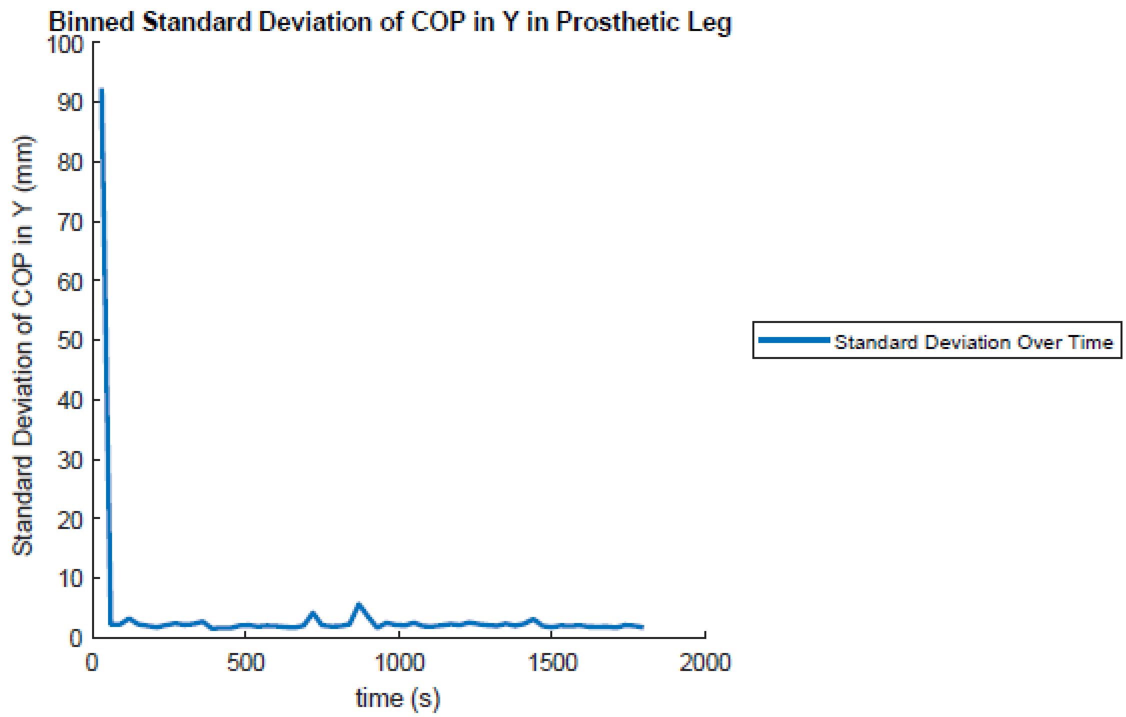
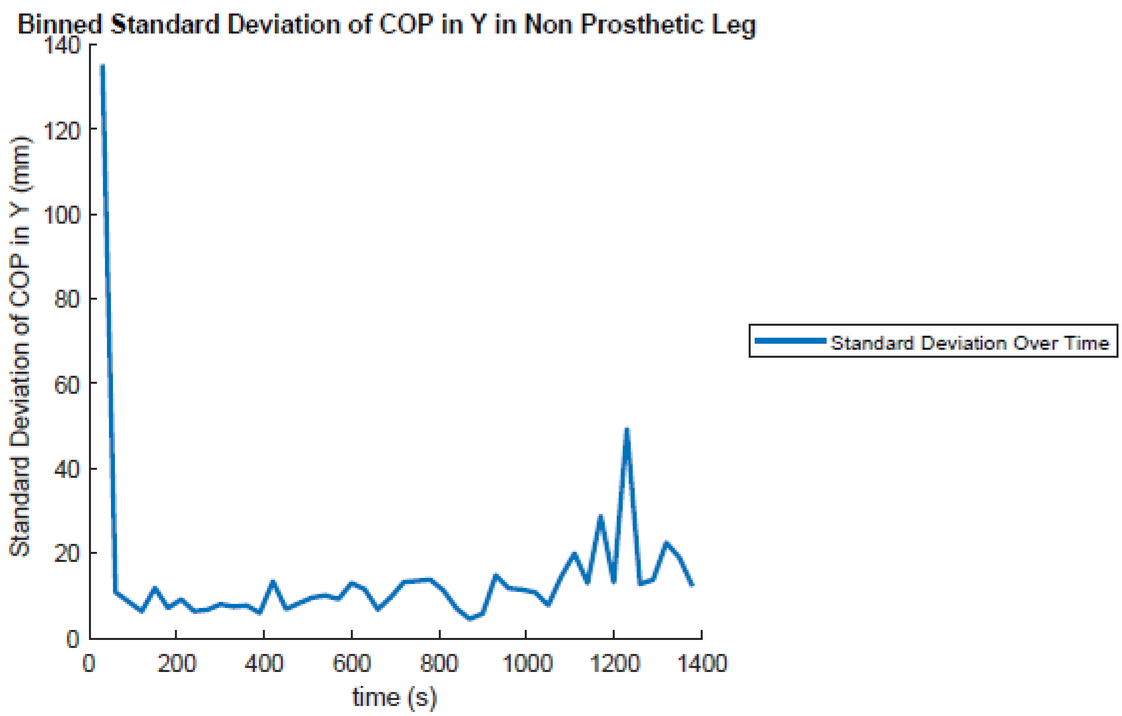


Figure 3.26: Standard deviation of COP Y over time for subject 4. The standard deviation decreased from the start of the trial to the end of the trial.



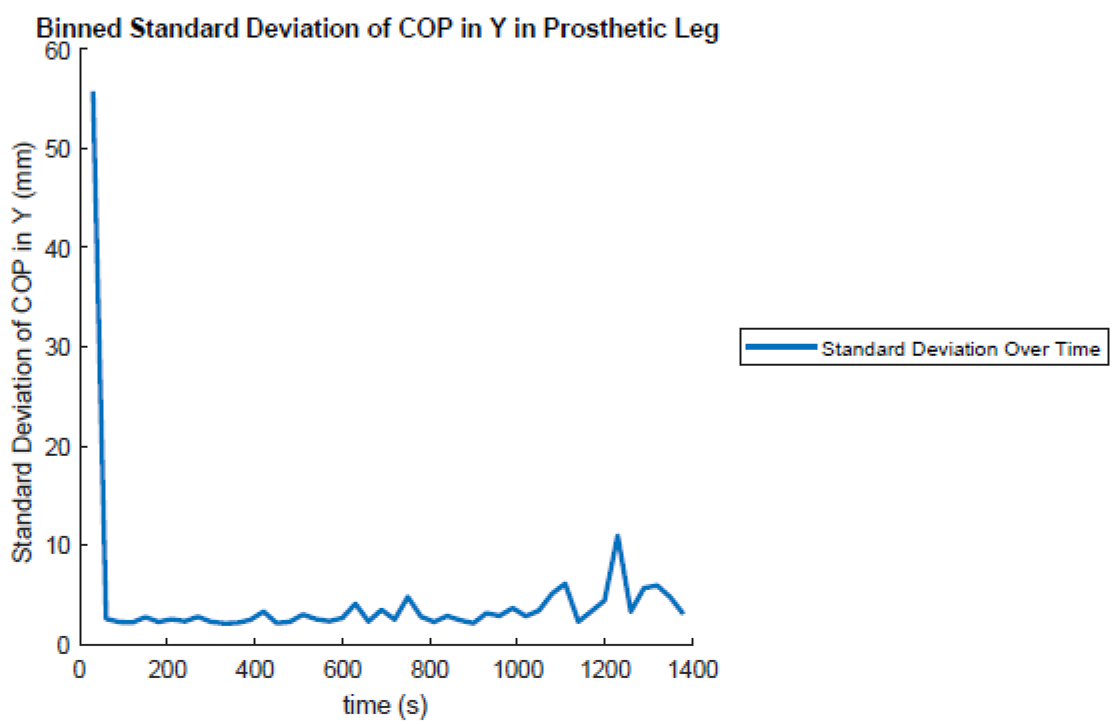
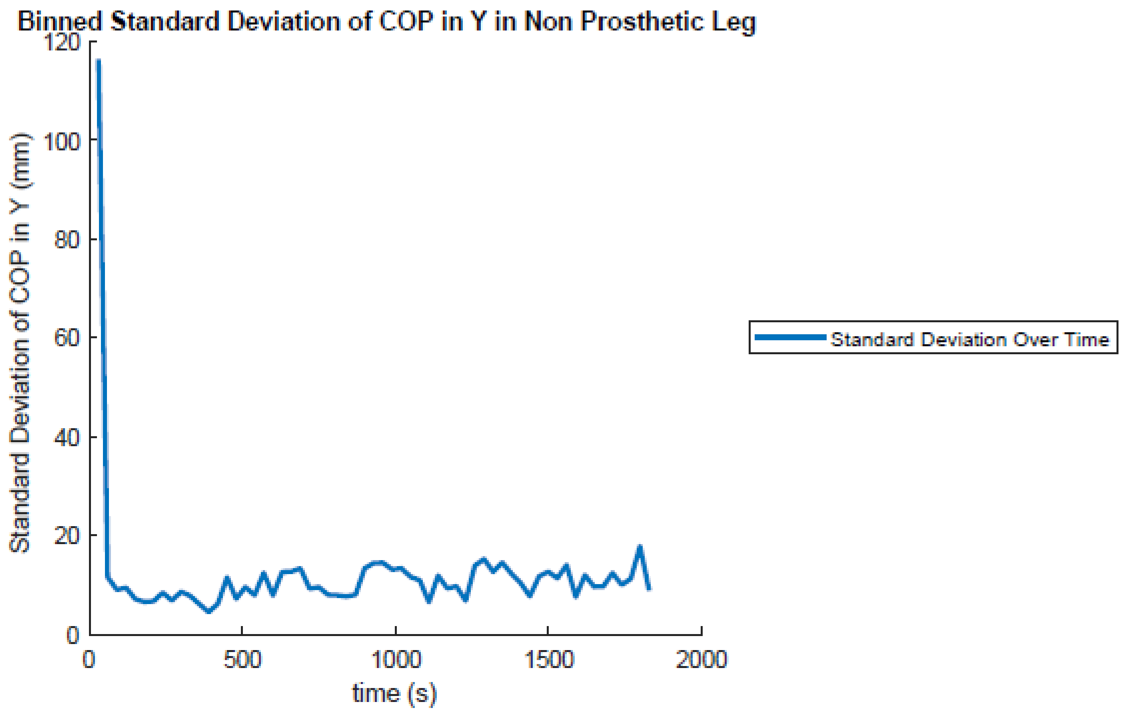


Figure 3.27: Standard deviation of COP Y over time for subject 5. The standard deviation decreased from the start of the trial to the end of the trial.



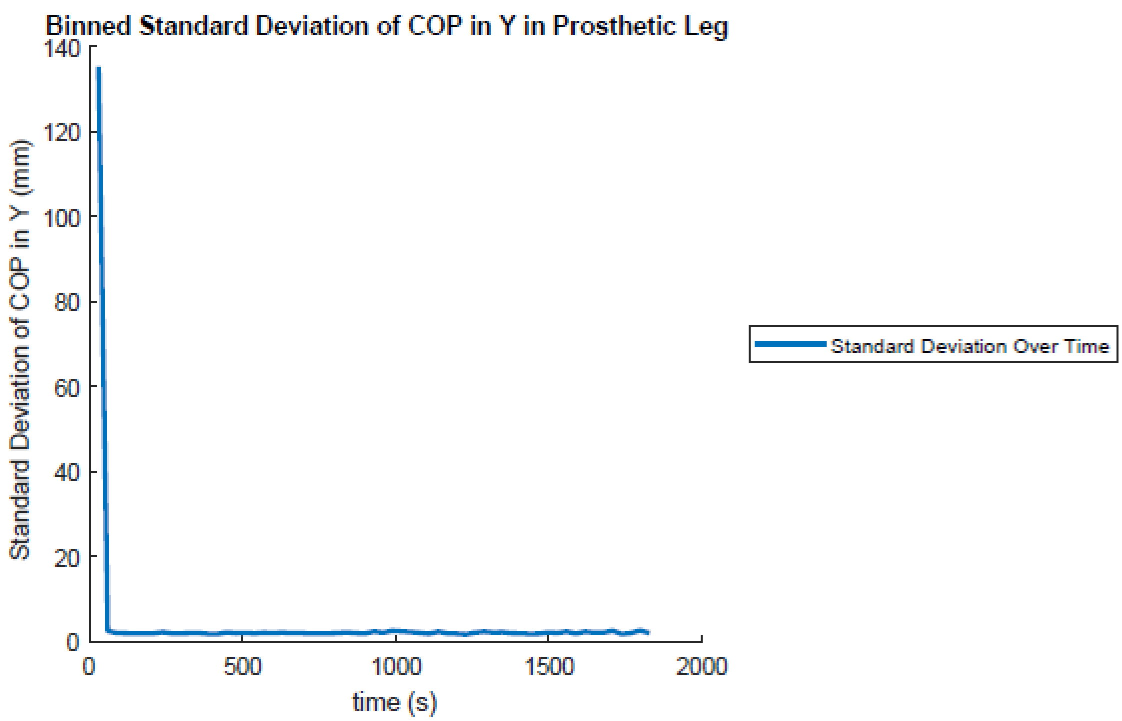
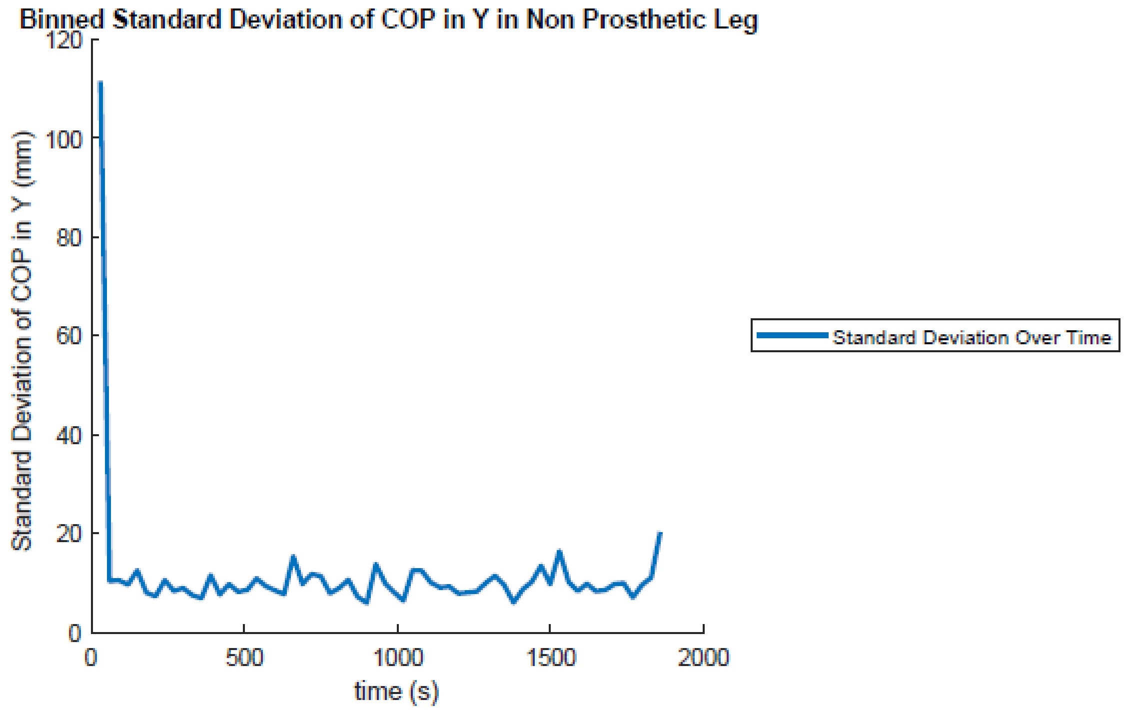


Figure 3.28: Standard deviation of COP Y over time for subject 6. The standard deviation decreased from the start of the trial to the end of the trial.



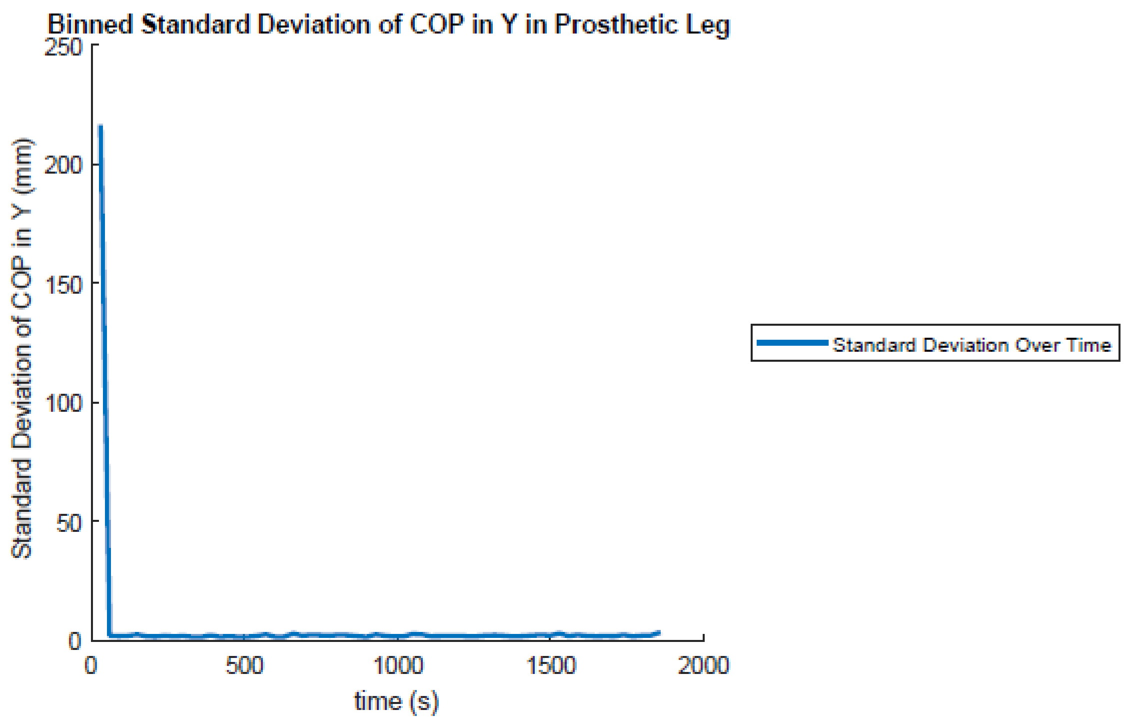
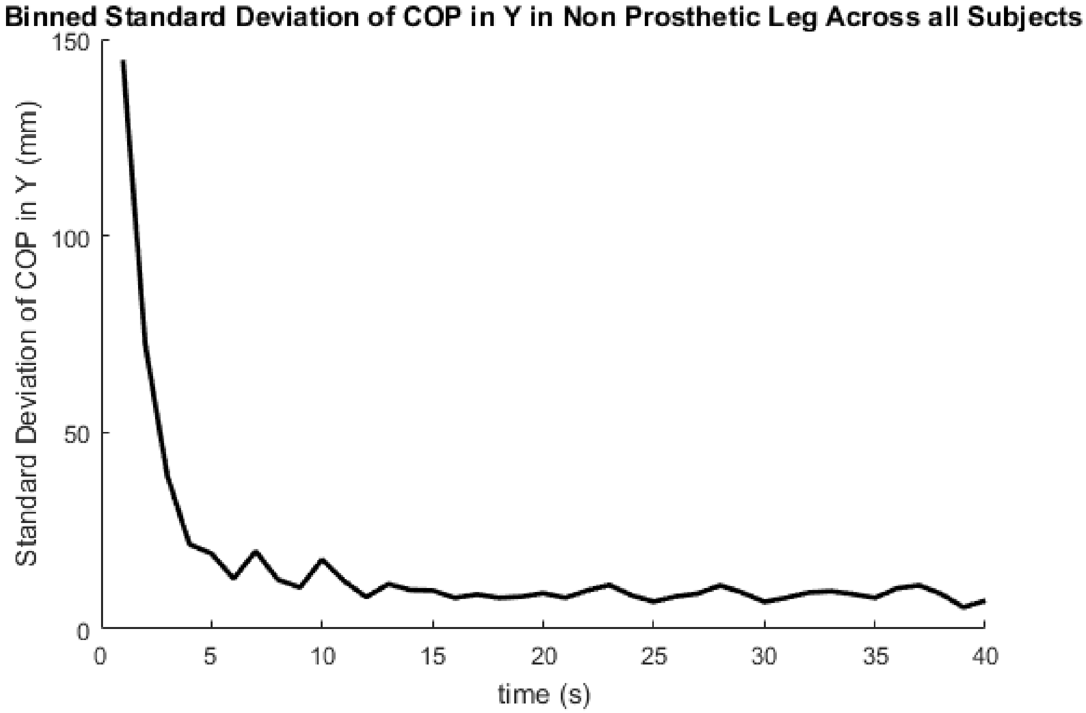


Figure 3.29: Standard deviation of COP Y over time for subject 7. The standard deviation decreased from the start of the trial to the end of the trial.

Center of Pressure Variability Across All Subjects Over The First 40 Seconds. Figure 3.30 shows the variability in the COP in the Y direction across all subjects, and Figure 3.31 shows the variability in the COP in the X direction across all subjects. The variability rapidly decreases in the beginning and then levels off. These figures support the above figures, showing that the learning period is early in the trial, as the variability levels off within the first 20 seconds of the trials.



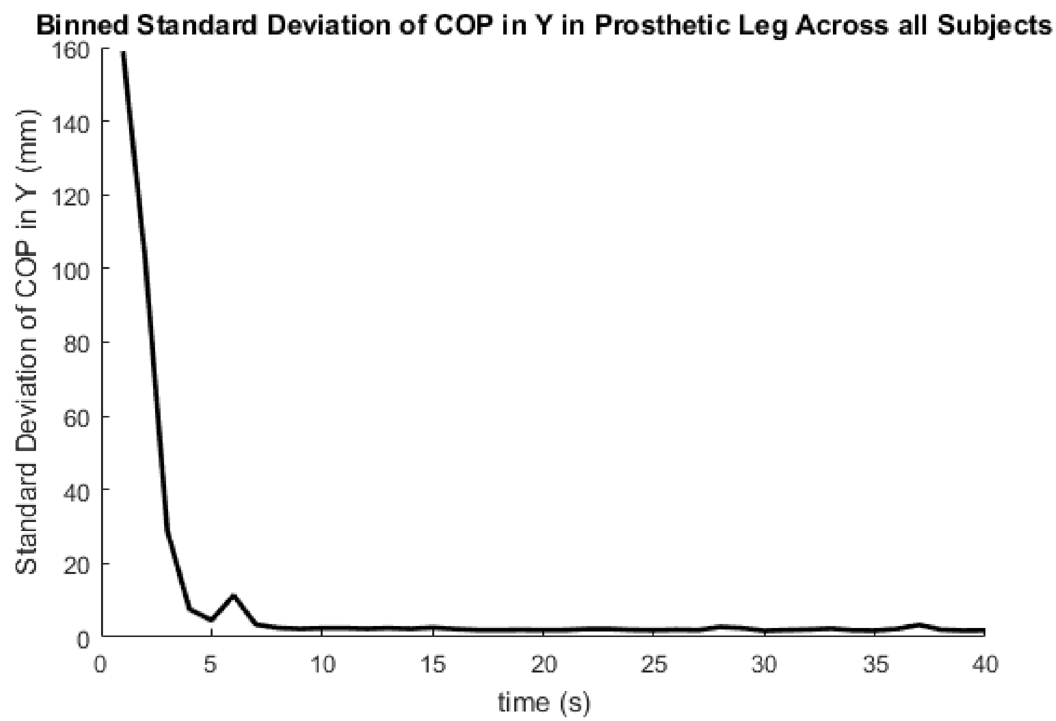
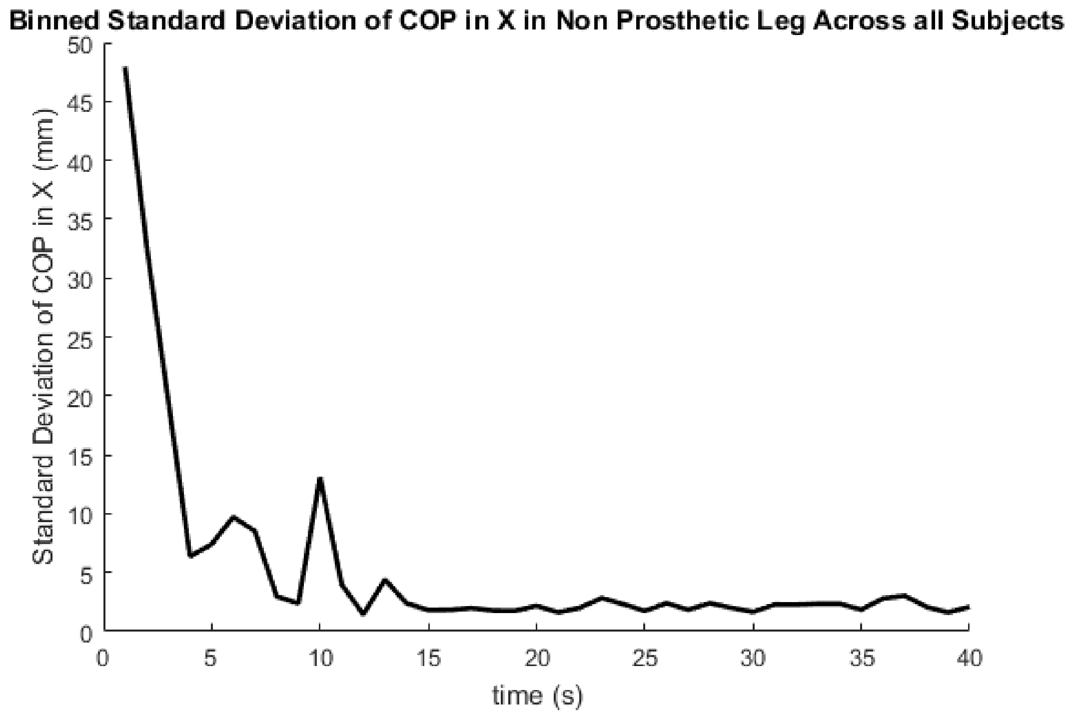


Figure 3.30: Standard Deviation in COP Y over the first 40 seconds averaged across all subjects. The standard deviation decreased rapidly at the start and leveled off within the first 20 seconds.



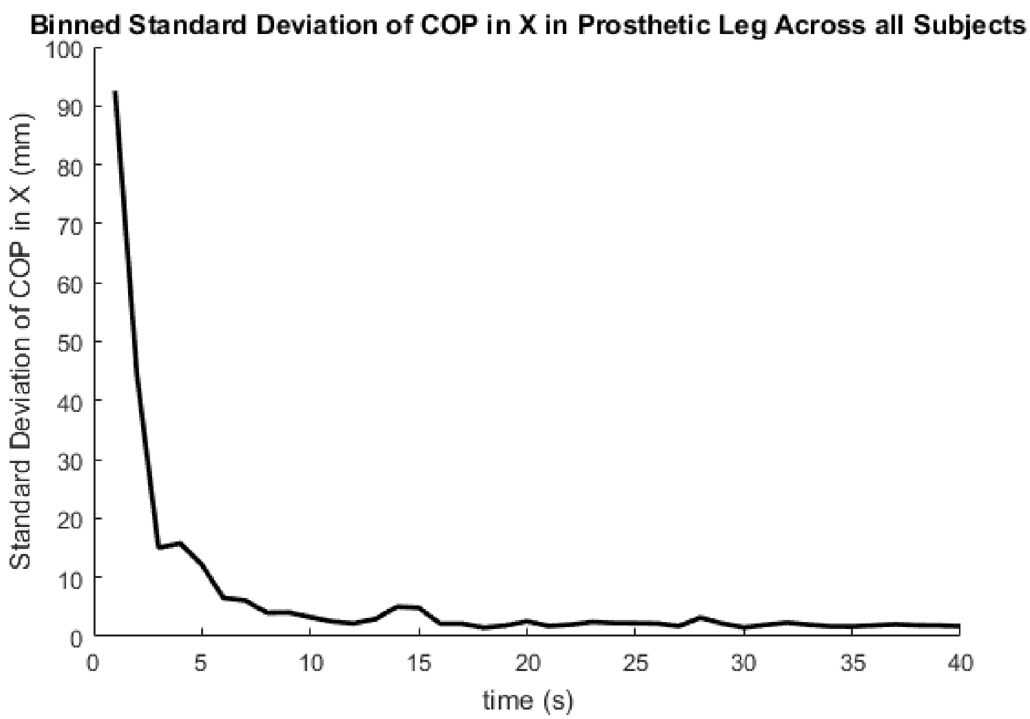


Figure 3.30: Standard Deviation in COP X over the First 40 seconds averaged across All Subjects. The standard deviation decreased rapidly at the start and leveled off within the first 20 seconds.

Chapter 4: Conclusion

This chapter describes the contributions, additional applications, future work and summary of the work done in this research.

4.1 Contributions

This research began the data collection on how humans learn to balance. From the data, we determined how humans learn to trust a simulated prosthesis, shifting weight from their non-prosthesis leg to the prosthesis leg over the course of 30 minutes. Over this time frame they become more stable, approaching similar standard deviations in various quantities that they would have without the prosthesis. Although their stability and standard deviations approach the same values as that the non-prosthesis trials had, their weight is distributed differently, but stably.

This study also showed that humans are able achieve these stable standard deviations in less than 100 seconds with the majority of the decreasing standard deviation occurring in the first 20 seconds, enabling them to balance even with changes to their lower body. This means that crucial learning period is within that first 20 second time-frame, and will be focused on in the model and future studies. A study of this nature has not been performed in the past, and so all of this data and results are a contribution to the field. The final contribution is the setup of the experiment. This experiment was able to collect data about the learning process and distinguish it from normal standing, so the setup could be used in other standing or balancing experiments focusing on the learning process. This is outlined further in section 4.2.

4.2 Additional Applications

This experimental approach has other uses than those outlined in this study. This experimental setup could be adapted to a walking study to monitor how subjects learn to walk by allowing the treadmill to move when the subjects reached a stable balance. We could then collect data on how their gait changes and learn about how the subjects learns to walk with an introduced prosthesis. In addition, during this study the motion capture data was largely unused, and so a procedure similar to this one that instead of focusing on ground reaction forces and center of pressure, could focus on similarities in body posture and the effect that learning to use a prosthesis has on that.

4.3 Future Work

For future work, first, a feedback-controlled dynamical model will need to be fitted to the data, as outlined in Chapter 2; this modeling work is currently ongoing and will be part of future work. With the model completed, more subjects would be required to better calibrate the model and better understand the range of learning across different subjects. The study originally called for 10 subjects, yet we only completed 7 subjects.

As noted earlier, we could build on the current standing study by performing a walking study. Using a similar procedure to this study, the subject would stand and balance. After the balance learning period had expired (which would be obtained from the model), the subject would then begin to walk on the treadmill. Data on their COP, reaction forces, step length, and body positioning would be captured and then the learning process of how someone learns to walk with a simulated prosthesis could be fit to a model. With these two models, one could begin to create an overall model of how humans learn standing, balancing and walking.

4.4 Summary

The process that humans use to re-learn how to stand upon wearing a prosthesis has not been studied prior to this research. Understanding how humans learn to stand can help treat amputees, stroke victims and other people with movement disorders learn to stand. In this study healthy adult subjects were fitted with a simulated prosthesis to force them to relearn standing and balancing. Using a force plate and Vicon 3D motion capture system data was collected on the subjects learning process. It was found that subjects approach a stable standing position of similar stability to their normal non-prosthesis standing, but with a different weight distribution. The subjects shifted their weight over the course of the trials from the non-prosthesis leg to the prosthesis leg. In addition, the subjects reached a stable standing position within the first 100 seconds of the trial, with the majority of the decrease in the standard deviations occurring within the first 20 seconds, suggesting that the learning period is done within the first 20 seconds after equipping the prosthesis. A model has not yet been fit to the data and will need to be done for future studies of this nature. The methods used in this study have applications to other studies in the field, in particular with studies on learning how to walk.

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